Global development of emissions reduction strategies from light duty vehicles

P Bielaczyc1,*

1 BOSMAL Automotive Research and Development Institute Ltd
E-mail: piotr.bielaczyc@bosmal.com.pl

Abstract. The automotive industry (especially the LDV sector) is currently under unprecedented pressure from a wide range of factors particularly in terms of environmental performance and fuel consumption. Long-established test procedures are changing and standards are becoming much harder to meet, necessitating changes in R&D methods, strategies and calibrations, fuels and – crucially – powertrains. This paper examines the current situation regarding regulation of emissions rules and the impact on powertrains used in new vehicles across the world. Powertrain technologies which can help to overcome challenges are mentioned and key trends are analysed. Finally, some brief comments are offered on what the next few years hold for the automotive industry.

1. Introduction

Despite decades of development in the automotive industry, vehicular emissions have been one of main sources suspected to contribute to adverse health effects and concern over the impact of vehicles on air quality remains high. In the world are over 1.5 billion motor vehicles today and that number may increase to 2 billion by about 2020. The transport sector is the biggest oil consumer, accounting for around 48 million barrels of oil per day [1]. The main drivers of current and future personal transportation development are presented in figure 1 [2]. Emissions of greenhouse gases from road vehicles remain very high on the political agenda; emissions of particulate matter and nitric oxides are coming under increasing scrutiny as a form of pollution with wide-ranging negative impacts; certain as-yet unregulated gaseous emissions are potential air quality risks. Looking to the longer term, the security of the oil supply and broader energy usage concerns have become very much part of the automotive development landscape.

Concern over gaseous and solid pollutants – perhaps most infamously CO₂ – has become a central issue for all major global markets, not just the United States and European Union. The major global automotive markets have all set exhaust emissions limits for new road vehicles, which have become increasingly stringent over the past few decades. There is also considerable pressure to reduce fuel consumption/fuel economy and CO₂ emissions – around 80% of all new light duty vehicles sold globally are subject of some kind of energy efficiency regulation. The European Union has planned the most challenging targets for reducing CO₂ emissions from light duty vehicles in the world. Passenger cars and light commercial vehicles now account for 13% of greenhouse gas emissions in the EU. But by 2021, CO₂ emissions from new cars coming onto the roads should be 42% less than the new cars in 2005 (over the NEDC test, under laboratory conditions). This is in fact ahead of the targets set by the EU for 2030. CO₂ emissions reduction has been achieved in conjunction with decreases in nitrogen oxides (NOₓ) by 90% and particulate matter (PM) by 84% through the introduction of the Euro 5 and 6 standards – despite these initiatives requiring conflicting measures[3].

Now, following revelations that emissions from real vehicle usage are generally poorly reproduced in the laboratory, test methods themselves are changing: first in the laboratory (e.g. the WLTP/C – GTR15; USA CFR 1065/1066 procedures); furthermore, real driving emissions have increased in importance to the point where RDE/PEMS measurements have become a legal requirement in the EU (from September 2017).
The introduction of particle number limits and increased scrutiny of particulate emissions from engine types other than Diesel represents a somewhat challenging direction in emissions testing and control. These factors exert massive pressure on vehicle and engine manufacturers (both light duty and heavy duty), their suppliers and the oil and fuel industries. Reduction of harmful emissions, today especially NOx for diesel LD engines and PN (particulate number) for gasoline DI engines are among the main drivers influencing personal transport development (figure 1) [4]. Other, allied fields such as catalytic converters, fuel, fuel additive and lubricant suppliers also find themselves subject to the same forces. Many of the aforementioned problems are shared by the various stands of the industry – passenger car and light commercial vehicle/heavy-duty/off-road/non-road/marine – and many of the proposed strategies and technical solutions have multi-segment applicability.

As a result of stringent regulations of regulated pollutants and greenhouse gases vehicle and powertrain technology is also developing very fast and new engines family as well as new powertrain systems will be present soon at the main automotive markets. However, the market is dictated not only by political and technical factors, but also by consumer demands, which are themselves also evolving. Something both legislators and the general public have in common is the goal of reducing fuel consumption, without any sacrifices in terms of vehicle drivability, durability or safety. Responding to this pressure, a broad range of advanced engine technologies, catalytic aftertreatment systems, revised fuel types, bespoke lubricants and friction inhibitors, etc. have been introduced. These strategies are often interrelated: low sulphur fuel is required for aftertreatment system compatibility; advanced engine design has impacts on required lubricant properties, etc. Fundamental changes to the propulsion strategy for on-road vehicles (e.g. fuel types/the implementation of advanced electromechanical systems – hybrids, development of new powertrain types as fully electric vehicles (BEV) or fuel cell) represent a revolution in the industry. All these advanced technologies must be developed, tested, approved and certified. In the case of hybrid or electric powertrains, accurately quantifying the real world CO₂ emissions benefit is of particular importance [5].

**Figure 1.** Main drivers of powertrain development.
2. Directions in GHG emissions reduction and CO₂ emissions legislation

Greenhouse gas emissions became a real issue several years ago already and many countries accepted rules to reduce CO₂ fleet average emissions for newly sold vehicles. New passenger cars sold in the European Union in 2015 emitted (over the NEDC) on average 119.6 g CO₂/km (10 g CO₂/km below 2015 target). 13.7 million new cars were registered in 2015 – a 9% increase in comparison to 2014. The EU wants to limit CO₂ to 95 g CO₂/km in 2021. The Global Fuel Economy Initiative (GFEI) “50 by 50” is an initiative jointly launched by UNEP (UN Environment Program), IEA (International Energy Agency), ITS (International Transport Forum), FIA Foundation. It calls for cars worldwide to be made 50% more fuel efficient by 2050, along with interim targets.

Official EU rules are:

- EC 443/2009 regulates the average specific emission of CO₂ for each manufacturer for NPC registered in EU in each calendar year
- Permitted CO₂ emissions = 130 g/km [NEDC] + 0.0457 * (vehicle mass [kg] − 1,372 [kg])
- 2020 target: 95 g CO₂/km in 2021 – application of WLTP after 2017.

Fleet average CO₂ standards have proven effective at reducing test-cycle emission levels of new vehicles in recent years, although a growing laboratory-road gap is in evidence. To meet agreed climate targets, the annual CO₂ reduction rate for vehicles coming to the market in 2020-2030 needs to be significantly higher than in previous years [2].

The European Commission’s Joint Research Centre carried out work to estimate the impact of the introduction of the new type approval procedure WLTP, on the European car fleet CO₂ emissions. To this aim, a new method for the calculation of the European light duty vehicle fleet CO₂ emissions, combining a simulation at individual vehicle level with fleet composition data is adopted. The method builds on the work carried out in the development of CO₂ MPAS, the tool developed by the Joint Research Centre to allow the implementation of European Regulations 1152 and 1153/2017 (which set the conditions to amend the European CO₂ targets for passenger cars and light commercial vehicles due to the introduction of the WLTP in the European vehicle type-approval process). Results show an average WLTP-to-NEDC CO₂ emissions ratio in the range 1.1-1.4 depending on the powertrain and on the NEDC CO₂ emissions. In particular the ratio tends to be higher for vehicles with lower NEDC CO₂ emissions in all powertrains, the only exception being with the plug-in hybrid electric vehicles (PHEVs). In such cases, the WLTP to NEDC CO₂ emissions ratio quickly decreases to values that can also be lower than 1 as the electric range of the vehicle increases[7].

On 7 July 2017, two new Regulations were published on the CO₂ correlation between NEDC and WLTP: Commission Regulation (EU) 2017/1153 for passenger cars and (EU) 2017/1152 for light commercial vehicles. As stated in those documents, the WLTP test procedure was to be phased in, starting with new vehicle types from 1 September 2017 and all vehicles from 1 September 2018 (for M and N1 vehicle categories). From 1 September 2019 all new vehicles placed on the EU market have to be tested for CO₂ and pollutant emissions according to the WLTP procedure [3].

On 8 November 2017, the European Commission presented its latest legislative proposal setting new CO₂ emission standards for passenger cars and light commercial vehicles (vans) in the European Union for the period after 2020. Average emissions of the EU fleet of new passenger cars and light commercial vehicles in 2030 will have to be 30% lower than in 2021. For 2025, targets for PC and LCV and vans are to be 15% lower than in 2021, so as to ensure that emission reductions occur as early as possible [6]. Starting from 2021, the emission targets will be based on the new emissions test procedure (the WLTP), which was introduced in European regulations on 1 September 2017.

Since 2008, the United States has experienced the first sustained period of rapid GHG emissions reductions and simultaneous economic growth on record. Specifically, CO₂ emissions from the energy sector fell by 9.5% from 2008 to 2015, while the economy grew by more than 10% [8].

Current official US rules are:

- 2 sets of parallel standards, namely:
  - CAFE – Corporate average standards adopted by NHTSA
  - GHG – Green House Gas standards adopted by EPA
- MY 2022 – 2025 - Mild Term Evaluation (MTE) made by EPA. The MTE will commence in early 2016 and issued a final determination by April 2018 with final standards to follow.
- EPA and CARB GHG regulations are harmonized from 2017-2025, but after changes in the American presidency and administration also changes in US GHG emissions policy are planned to be introduced.
- Other countries with CO₂ (or fuel/energy consumption/economy) limitations: Japan, Brazil, PR of China, South Korea, Taiwan.

3. Changes in global emissions rules as a main driver for powertrain development

3.1. General approaches of modern emission standards

After about 50 years of vehicles’ emissions regulation and control, today there are many different emissions standards, test procedures and limits obligated for the main automotive markets such as the EU, the USA, Asia (mainly Japan, China and India) (Figure 2). In all cases, emissions standards are built on four pillars: tailpipe harmful pollutant limits; test procedures that describe the testing methodology; a driving cycle to be performed on a chassis dynamometer in an emissions laboratory under prescribed test conditions; and equations describing the calculation of test results [9]. Global harmonization of automotive emissions regulations remains a distant prospect, but it is now often mentioned that harmonization of emissions procedure and protocols could bring benefits for automotive OEMs and customers – customers today are not getting value from region-to-region variation [10]. The first step in this direction could be UNECE GRPE programme on introduction of World Light-duty Vehicles (harmonized) Test Procedure WLTP that was carried out over 2007-2015 (for the first step) by the EU, Japan, India, China, and Korea, with the support of other countries (including the USA) and finalized via a new UNECE emissions regulation (GTR15, published in 2014) that defines the test procedure based around the WLTC.

![Figure 2. Development trends in emissions regulation on the main automotive markets.](image-url)

Regarding the test cycle and the technical specification, in line with a “split level approach”, limits will be set during the transposition to national legislation in the EU and some Asian countries. The latest version of GTR 15 is described in the Proposal for Amendment 3 to global technical regulation No. 15 (WLTP) and was submitted by the Informal Working Group on WLTP at the 75th GRPE ECE session at United Nations in Geneva in June 2017 [11].
3.2. European Union

Despite intensive work carried out in the past few years by the introduction of Euro 4, 5 and 6b emissions regulation in the European Union, currently vehicles present on European roads have shown much higher emissions during real on-road driving under real-life operating conditions than in the standardized type approval tests performed under laboratory conditions. The emissions test procedure based on the NEDC cycle performed on the chassis dyno according to Regulation (EC) 715/2007 was outdated not only because of its unrealistic test cycle, but mainly because of the incorrect setting of chassis dyno parameters in road load determination procedure and vehicle inertia simulation (Table 1). As a result, especially Diesel vehicles’ tailpipe NOx emissions and gasoline vehicles’ PN emissions were higher during measurement on the road than in the laboratory measurement [12], [13].

Table 1. The dead hand of the past – outdated EU procedures.

| Aspect                                      | Effect                                                                 | Solved? How?                                      |
|---------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------|
| Undemanding test cycle (NEDC)              | Lower regulated emissions, somewhat lower CO₂/FC                        | Yes, via WLTP and RDE                             |
| Single laboratory cycle used                | Test cycle can be “targeted”                                           | Yes, via RDE                                     |
| Vehicle inertia categories used             | Vehicle weight can be manipulated to achieve a lower inertia setting → lower regulated emissions, CO₂ and FC | Yes, via WLTP (categories abandoned, stepless approach adopted with resolution of 1.0 kg instead of 110 kg a la NEDC) |
| Vehicle weight definition includes very limited payload | Lower inertia setting (as above)                                       | Yes, via WLTP (+15% of maximum payload added to passenger car weight definition; +28% for vans) |
| Road load determination (coast down) procedure loopholes | Unrealistically low running resistance → lower CO₂ and FC, regulated emissions | Yes, via WLTP (loopholes mostly closed); for RDE real world road load applies |
| Battery state of charge unusually high (normally charged to 100% before test) | Lower CO₂/FC (and even regulated emissions) in cold start phase of test | Yes, WLTP explicitly prohibits charging battery before emissions test; *situation for RDE unclear (?)* |
| Electrical accessories turned off           | Lower CO₂/FC (and even regulated emissions), especially in cold start phase of test | Yes, RDE permits use of accessories to reflect normal driving practice; *WLTP may include in the future (?)* |

On 16 December 2015, the European Parliament decided to set up a Committee of Inquiry to investigate contraventions of EU law in relation to emissions measurements in the automotive sector and maladministration in its application. The Inquiry Committee was set up in reaction to the revelations that Volkswagen Group dodged the NOx (Nitrogen oxide) emissions limit for diesel cars. This Committee conducts surveys, send letters, holds hearings, etc. As a first step, the findings of this body is presented in a Draft Report [14]. The main conclusions from this report are following:

- There are large discrepancies between the NOx emissions of most Euro 3-6 diesel cars measured during the type-approval process (TA) with the NEDC laboratory test, which meet the legal limit, and their NOx emissions measured in real driving conditions (RDE), which substantially exceed the limit.
- The mandate for the Commission to improve the current TA procedure resulted in the development and introduction of real driving emission (RDE) testing with Portable Emission Measurement Systems (PEMS) into the EU TA procedure as of 2017.
The new framework for vehicle type-approval proposed by the European Commission would harmonise enforcement practices across EU member states and – crucially – shift the focus from pre-production to in-service conformity and market surveillance.

The latest emissions standards were presented in the Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008. The main issues for Euro 6 regulations are the following:

- Euro 6c - Full Euro 6 emission requirements but without quantitative RDE requirements,
- Euro 6d-TEMP - Full Euro 6 emission requirements, with RDE testing with NTE limits based on temporary conformity factors;
- Euro 6d - Full Euro 6 emission requirements, with RDE testing with NTE limits based on final conformity factors [15].

On February 28th 2017 the final inquiry into emission measurements in the automotive sector was approved. The European Parliament issued its recommendation to the Council and the Commission following the inquiry into emission measurements in the automotive sector (EMIS) on April 4th, 2017. Both the report and the response to it are critical of the slow rate of progress in tackling the topic of real driving emissions and laboratory-road gaps. The parliament’s recommendation calls for a wide range of changes to be made in response – if enacted, they would radically change the vehicle type approval process. Increased market surveillance and auditing of emissions control strategies seems a certain outcome.

In June 2017 the latest emission regulations were introduced in the European Union and published in the Official Journal on 7th July 2017. They are:

- Commission Regulation (EU) 2017/1151 introducing the new World harmonized Light vehicle Test Procedure (WLTP) and amending the implementing Euro 5&6 Regulation (EC) No 692/2008 with the new WLTP-based Type I test [16],
- Commission Regulation (EU) 2017/1154 amending Regulation 2017/1151 and introducing the third Real-Driving Emissions (RDE) Act -introduce the test protocol and limits for measuring real-world particle number (PN) emissions, taking account of periodic regeneration events [17].

3.3. USA (including California)

In general it can be stated that California is the “home” of exhaust emissions legislation and control, with the Californian approach continuing to influence the rest of the US and the rest of the world. As early as 2007, fourteen US states other than California had implemented Californian legislation (at least in part). Tier 3 emission standards were adopted in March 2014 with phase-in 2017-2025. The regulation also tightens sulphur limits for gasoline.

Both the certification limits (Bins) and the fleet average standards are expressed using the sum of NMOG+NOX emissions. The required emission durability has been increased to 150,000 miles or 15 years, whichever comes first. Gasoline vehicles are tested - for exhaust and evaporative emissions - using gasoline containing 10% ethanol (E10).

California applied emissions standards called LEV. LEV III standards were finalized in December 2012 with phase-in 2015-25. Beginning 2020 all vehicles need to be certified to LEV III[18].

California has a waiver to set its own emissions standards, which are more stringent than the federal (EPA) equivalents. In President Obama’s era Californian ARB standards were tolerated and even adopted by other states, meaning that 1/3 of the US population lived in a state where CARB standards were in force. CARB influenced EPA legislation and there were moves towards convergence on criteria emissions and GHG emissions. This was in line with Obama’s general approach to energy and emissions. Donald Trump came to power promising to stop environmental regulations from restricting business and in March 2017 vowed to loosen vehicular emissions legislation. President Trump even considered completely disbanding the EPA. CARB and some other parties are resisting this direction and CARB is pressing ahead with more stringent emissions requirements for vehicles. CARB’s waiver may be revoked – but legal battles could last for
years. California was the starting point for automotive emissions legislation and CARB legislation has influenced the rest of the US and the rest of the world – any changes in California are important.

3.4. China, India and Japan

China, which has become the largest global automotive market, has introduced a very ambitious emissions reduction programme since 2013 that has led to significant reductions in automotive emissions, especially in large urban agglomerations, by introducing China Stage 6 rules similar to Euro 6, introducing also more dynamic WLTC cycle and WLTP rules. China plan to adopt also real-world driving emission testing based on the European one, but with modification that address the unique driving conditions in China (extremely wide range of altitudes and ambient temperature/humidity). Testing includes 7 types of tests, i.e. at various ambient temperatures, the agency decides which of them manufacturers must perform to gain approval. The implementation of Stage 6 is divided into two phases. The China 6a standard will take effect beginning on 1 July, 2020. Implementation of Stage 6b is predicted for 2023[19].

India is following the EU emissions reduction programme via the introduction of BS IV (Bharat Stage 4), BS V and BS VI rules (which are similar to Euro 4, Euro 5 and Euro 6), with an intermediate phase between BS V and VI as short as possible (figure ). India plans to introduce RDE rules for type approval and COP tests from 1st April 2023. The RDE performance shall be demonstrated by testing vehicles on the road operated over their normal driving pattern, conditions and payloads [20].

Japan has its own emissions regulation named “Post new long term regulation” and its own Japanese test cycle – JC 08, which replaced the old Mode 10.15 and Mode 11 test cycles). Japan is also very active at the UN ECE GRPE informal group that is developing the new WLTP test procedure with the intention to implement the WLTC test cycle and the entire WLTP procedure in Japanese emissions regulation. (As Japanese traffic and speed limits do not permit the high speeds typical of European/North American motorways, the Extra High phase of the WLTC will not be used for testing in Japan.). Japan appears to be planning to increase the Diesel NOx limit for the WLTP.

Japan also plans to implement RDE regulation in 2022 and NOx is planned to be the only component with a not-to-exceed limit. The Japanese government plans to introduce a conformity factor CF 2.0, but it will be considered to reinforcement of CF values and addition of target component, based on technological development trends and international trends [20].

4. Development of emissions test methods

4.1. New light duty world harmonized test procedure – WLTP

In November 2007: the World Forum for Harmonization of Vehicles Regulations (WP.29) of the UN ECE on GRPE session established an informal group to prepare a road map for the development of a World-harmonized light-duty vehicle test procedure (WLTP). The development of the WLTP comprised two main elements:

a) Development of a harmonized driving cycle representative of world average driving conditions (internally referred to as the DHC - Informal Subgroup on the Development of the WLTP Test Cycle),

b) Development of a harmonized test procedure that sets the conditions, requirements, tolerances, etc. for the emissions test, test equipment and instruments (internally referred to as the DTP - Informal Subgroup on the Development of the WLTP Test Procedure).

The term ‘WLTP’ has been in use for some years, but very recent developments and formalisations in the development of this programme mean that it in fact it is use only as unofficial name. GTR15 (‘Global Technical Regulation No. 15’) has come into being and so ‘GTR 15’ is now a more appropriate term for developments and planned implementations in this area. The main planned target is regarding CO₂ emissions and fuel consumption, since for at the Euro 6 level emissions limits for regulated pollutants are not cycle-specific.
Currently EU institutions are working on transposition and implementation of WLTP regulation from UN ECE GTR15 to European legislation. In the EU the WLTP is being prepared as a new implementing and amending regulation of co-decision EC No. 715/2007 that will eventually replace the current EC No. 692/2008 (NEDC). The WLTP was introduced via Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008 and further corrected by Commission Regulation (EU) 1347 of 13 July 2017. This new Regulation has also change the emission type definition for vehicles in this way that any first time official emissions testing of vehicles for the WLTP inevitably creates new emission type approvals (TA), regardless of whether the vehicles have already a previous emission type approval according to the implementing provisions of Regulation (EC) 692/2008 or not.

It means that vehicles type approved to the WLTP after 1 September 2017 will have to comply with RDE requirements (PEMS testing), with step 1 not-to-exceed (NTE) emission limits. Since type approval to the WLTP is mandatory for all new vehicles as from 1 September 2018, all vehicles not fulfilling the RDE step 1 requirements would have to be tested for the WLTP before 1 September 2017 or could not be sold anymore after 1 September 2018.

The new test cycle WLTC (World Light-duty Test Cycle) that is introduced in WLTP regulation and is already specified in GTR15 is very different from the current NEDC cycle as it is more transient and somewhat similar to the US FPT-75 cycle.

The WLTC trace is much more ‘RDE-like’, but it remains a laboratory cycle designed for testing a wide range of vehicles (city cars to luxury SUVs and sports cars). Changes in the definition of vehicle mass generally leads to higher chassis dyno inertias, which tend to increase regulated emissions (notably NOx) and CO2. A new WLTP methodology requires many modifications in the emission test procedure as well as in the emission testing laboratory. The most important of them are [10]:

I. Related to the test cycle:
   - WLTC (Worldwide harmonized Light duty Test Cycle)
   - Different for 4 vehicle classes, depending on the power/weight ratio and max. speed

![Figure 3. Comparison of NEDC, WLTC and RDE - operating conditions of a vehicle in road tests: vehicle speed, engine load and rpm.](image-url)
o More dynamic, less idling, longer (20 → 30 min), higher average speed (34 → 46 km/h avg. and higher max speed (120 → 131 km/h).

o Individual shifting points for each vehicle for manual transmissions.

II. Related to road load simulation for testing

- More realistic road load determination and simulation, to eliminate fuel consumption optimization.
- Test of a “Low CO₂” and “High CO₂” vehicle per vehicle family and interpolation
- Electrical energy flow evaluated for the 12V vehicle battery.

III. Vehicle preparation and conditioning

- 23°C test and soak temperature. +/-3°C (5 min running average) during soak, +/- 3°C at test start and 5°C during the test (2Hz data).

IV. Test and measurement procedure

- Bag analysing sequence optimized (calibration and checks once per test run)
- PM/PN measurement using dilution tunnel, particulate filters and number measurement for gasoline engines as well, PM/PN Background correction (optional).

4.2. Real Drive Emissions (RDE)

The need to have stable test conditions and for results to be reproducible in any suitably-equipped laboratory was considered a strong enough argument for automotive emissions legislation to only apply in laboratory contexts. So far being in force regulations are not enough in achieving the general goals of reducing harmful emissions and fuel/energy consumption pointing out to the "laboratory-road gap". This drove the further research on real drive emissions (RDE) standing for driving like a ‘normal’ driver and measuring the emissions.

RDE tests are carried out applying the Portable Emission Measurement Systems – PEMS (Figure 4) which should be conformed according to the Regulation (EU) 2016/427 of 10 March 2016. PEMS enables to measure the real emissions of CO, NO, NO₂ and CO₂.

![Figure 4. PEMS system installed in LCV during laboratory chassis dyno and on road tests.](image-url)
Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC of the European Parliament and of the Council as regards real-driving emissions from light passenger and commercial vehicles (Euro 6) [16], [17].

RDE is intended to exist in parallel with WLTP legislation and measurements will be carried out in on-road driving with different conditions. Emissions which will be evaluated in RDE testing of LDV are: NOx, CO, PN and CO2. The similarities and differences of RDE and WLTP tests are summarized in Table 2.

| Table 2. Comparison between RDE and WLTP test methods. |
|--------------------------------------------------------|
| **RDE** | **WLTP** |
| **Similarities** | **No constant speed** |
| Limited constant speeds | Limited idling time |
| Variable idling time | Variable acceleration rates |
| Variable acceleration rates | Comparable (or slightly lower) severity |
| Divided into stages | Divided into stages |
| Similar or even better “severity” of the test (especially in case of extended RDE) | Commences with urban-type driving (<60 km/h) |
| **Differences** | Realized on a carefully-controlled chassis dyno |
| Emissions related with real-life conditions | - better repeatability |
| Road profile, road surface quality, ambient conditions, traffic congestions and driver’s behaviour (eco-driving, neutral, aggressive) determine final parameters of the test (constant speeds, acceleration rates) and final emission levels - worse repeatability | Less dependent on external factors |
| Ideal flexibility (usage of all gears) | Customized gearshifts – good flexibility |
| Complex procedure of data acquisition, post-processing and final validation | Commences from cold start (albeit with relatively low weighting) |
| Cold start excluded (for the time being…) | Battery SOC monitoring & correction (but only for CO2/FC) |
| | Relatively simple CVS-bag measurement procedure (<1 hour/test) |
| | Work performed by the engine always the same in repeat tests |

The European Union plans to introduce new measures to protect using defeat devices by car manufacturers in vehicles by the introduction of changes in the type approval procedure and market surveillance tests [Kurt]. According to EU Guidance to the application of Regulation EC 715/2017 on type-approval of motor vehicles, defeat device recognition for member state surveillance testing is proposed as follows:
- Manufacturer declaration that the vehicle does not contain any defeat device,
- Extended Auxiliary Emissions Strategies (AES) with software version and checksums,
- Type approval evaluation and acceptance of AES,
- Testing for defeat devices (with the need to keep a non-predictable character)[22].

The European Council agreed on 29.05.2017 on a general approach to reform the system of type-approval and market surveillance for motor vehicles by:
- Screening the environmental performance of vehicle fleet by remote monitoring with Simplified Emissions Measurement Systems (SEMS) and remote sensing devices (RSD) at fixed locations or with chasing vehicles,
- market surveillance - by carry out spot-checks on vehicles already on the market in order to detect failures at an early stage,
- governance of the type-approval system - by creating a forum for representatives of relevant national authorities who would exchange information on enforcement [9].

5. Engine technology developments trends in light of emission rules changing

Despite high pressure for vehicle powertrain electrification, it is confirmed by many experts from the EU, USA and Asia that internal combustion engines (ICEs) as single powertrain system or in hybrid powertrain solution remain the main solution for transportation needs (especially for LDV), despite several countries (France, Great Britain, China, California) planning to end sales of gasoline and Diesel cars by 2040. Considerable progress has been made in reducing emissions and fuel consumption, but these goals need to be harmonised and pursued simultaneously, with "engine + aftertreatment + fuel + lubricant" considered as a single system, along with all interactions between elements of this system. Changes in world-wide emissions regulations, especially the introduction of WLTP and RDE, first in the EU, perhaps later also in other countries/areas, will lead to major changes in engine technology, control strategy and calibration. The test cycle is an important change (particularly given the differences between the WLTC and the NEDC), but the test cycle is only part of the story. More important are changes in testing conditions, especially road load simulation, inertia setting, etc.

But the new RDE test method introduced from September 2017 will have an even higher influence. To make an engine RDE-compliant can mean higher fuel consumption (and thus higher CO₂ emissions); RDE standards are a challenge that require the introduction of additional technologies to meet NTE requirements while keeping fuel consumption at the same level (or even simultaneously reducing it).

The trend for past few years has been one of downsizing (reduction of engine displacement, number of cylinders, dimensions and overall weight), as a consequence of CO₂ reduction trend is introduced in a synergy of many other technologies, such as: direct injection technology for both CI and SI engines, modulation of the compression ratio (variable CR), boosting technology – mainly 1-or 2-stage turbocharging, optimization of the engine’s controlling algorithm by adding many new parameters that influence the calibration, valve actuation technology, special dedicated exhaust aftertreatment systems as a combination of multiple different catalysts/traps or specially catalysed filters like SDPFs (Figure 5) [10].

![Figure 5. Engine technology trends – downsizing and a summary of the past few years.](image-url)
However, today engine manufacturers have to move from engine downsizing to engine rightsizing (in effect increasing the engine size and sometimes number of cylinders) in order to be able to meet RDE requirements with low CFs – particularly for NOₓ (Figure 6) [2].

![Engine technology trends diagram](image)

**Figure 6.** Engine technology trends – from free sizing to rightsizing and technology transfer between CI and SI engines.

There is still a considerable scope for downsizing engines for LCV – it can help with FC, CO₂, weight (and even NOₓ). Some downsizing for passenger cars remains possible as well, even in the era of WLTP/RDE, however, it must be carefully considered and tested and it is more applicable to SI engines than to CI engines.

Cylinder deactivation (displacement on demand) could be an attractive way to reap the benefits of smaller displacement without suffering the problems experienced in recent years – rightsized engine with the option of reducing cylinders/displacement at low load. Parallel hybrid powertrains add the flexibility of an additional power source to be used when demand for power is high. From a technical and economic perspective, stronger CO₂ reduction efforts are feasible: a 70 g CO₂/km target (over the NEDC) for new cars by 2025 can be reached largely without full electrification; however, the greater the number of battery electric vehicles, the easier it will be for manufacturers to meet the demanding fleet average CO₂ limits [3]. The main hybrid solution to meet this target will be a mild hybrid powertrain system (MHEV). MHEV systems contain a 48 V electric installation with a Li-ion battery and a BAS system (Belt Alternator Starter) that supports warm start-up. The standard starter will be used for engine cold-start only. Many new engines coming to the market already in 2018/2019 will be equipped with this system.

Diesel engines’ future will be decided by politicians and perhaps the public, not by engineers. Some NGOs’ reports reach some very negative conclusions on Diesel-powered passenger cars. Several countries and some cities (Paris, Athens, London, Madrid, Mexico City) may arbitrarily ban the Diesel engines, regardless of the environmental performance of WLTP/RDE-compliant Diesel powertrain. This is unfortunate, because the Diesel cycle is much more efficient than other work cycles, capable of reaching 55% thermal efficiency. Modern SI DI engines still emit more CO₂ than Diesel engines of the same power. Much published RDE testing carried out according to RDE packages 1 and 2 (not including the cold start) unfairly benefits petrol-fuelled vehicles and penalises Diesel-fuelled vehicles. RDE-PEMS test results are widely disseminated and discussed, but few outside the automotive industry have the technical insight to fully interpret the meaning of such results.

It seems that due to high political pressure and – on the other hand – the necessity to introduce SCR (or SDPF) systems to all CI engines, even in small passenger cars, because RDE tests with low NOₓ
CF virtually forces adoption of SCR system for all Diesel cars, the dominating engine technology will be SI gasoline engine with direct fuel injection (DI) system[19]. In the case of gasoline engines (SI) in LDV the main catalyst technology used to emissions control is Three-Way Catalyst (TWC) that operates in a close-loop system including a lambda or oxygen sensor to control the air-to-fuel ratio in SI engine. TWC is efficient solution for gasoline port fuel injection engines (PFI), but in case of direct-injection engines (DI), which are promoted in EU due to their better fuel efficiency, this solution can’t be sufficient to meet new Euro 6c PN limit of $6 \times 10^{11}$ #/km. Meeting this limit using the WLTP (instead of the NEDC) and also under RDE conditions (now including the cold start event, even where performed at low ambient temperature) makes the challenge harder still and constitutes even more pressure to implement a well-designed GPF.

Most of the vehicle OEMs in Europe already announced that all SIDI LDVs produced from 2017 will be equipped with GPF filter. Among them are: PSA, VW, Mercedes, BMW, FCA and Renault.

Still GPFs need to be improved taking into account parameters as design and microstructure of the filter, soot storage abilities, efficiency of passive regeneration and ash handling. The construction and operating regime of GDFs is surprisingly different from that of their Diesel-specific counterparts (DPFs):

- normally very little available oxygen ($\lambda_1$)
- high PN of low mass
- quick “passive” regeneration possible at fuel cut-off ($\lambda >> 1$)
- engine requires very low back pressure.

6. Conclusions

As a result of the topics explored in the preceding sections of this paper, certain conclusions can be drawn, bearing in mind that the currently situation in the vehicle and powertrain development is highly dynamic and that the pace of change is very rapid. Namely:

- Simultaneous reduction of fuel consumption, NO$_x$ and PM still remains a challenge – the WLTP and RDE will mean that substantial changes are required in order to meet the same Euro 6 emissions limits under much more demanding conditions.
- The relatively sudden introduction of WLTP and RDE in a short space of time is a shock for the industry, but not a fatal shock. However, certain powertrain options and technology combinations will be killed, or at least become rare.
- The era of widespread downsizing with aggressive turbocharging is over. Manual gearboxes may become less widespread because of RDE requirements.
- From the technical/engineering point of view, the Diesel engine can have a future – aftertreatment systems exist which can give CFs < 1 in RDE tests.
- Efforts to reduce emissions and fuel consumption under virtually all operating conditions need to be harmonised and pursued simultaneously, with engine/aftertreatment/fuel/lubricant considered as a single system.
- The full and final introduction of RDE and further WLTP topics (e.g. low temp test, additional pollutants) are ongoing. Other jurisdictions are watching developments in the EU closely. Some developing countries which have significant problems with urban air quality might decide to adopt WLTP and/or RDE procedures.
- Political, legal and technological shocks (“disruptors”) as fuel prices, advance battery cost for electric vehicles, international trends matter (i.e. USA emission rules) can disrupt the status quo and make predictions inaccurate.
### List of abbreviations

| AES                  | Auxiliary Emissions Strategies | NHTSA | National Highway Traffic Safety Administration |
|----------------------|--------------------------------|-------|-----------------------------------------------|
| ATS                  | Aftetreatment system           | NMOG  | Non-Methane Organic Gases                     |
| BS                   | Bharat Stage (India)           | NPC   | National Population Commission                |
| CAFE                 | Corporate Average Fuel Economy | NSC   | Nitrogen Storage Catalyst                     |
| CARB                 | California Air Resources Board | NTE limits | Not-To-Exceedlimits                           |
| CF                   | Conformity Factor              | OBD   | On-Board Diagnostics                          |
| CRF                  | Code of Federal Regulations    | OEMs  | Original Equipment Manufacturers              |
| CI                   | Compression Ignition engine    | PC    | Passenger Cars                                |
| DI engines           | Direct Injection engines       | PEMS  | Portable Emissions Measurement System         |
| DISI                 | Direct Injection Spark Ignition engines | PFI | Port Fuel Injection engines                   |
| DOC                  | Diesel Oxidation Catalyst      | PM    | Particulate Mass                              |
| DPF                  | Diesel Particulate Filter      | PN    | Particulate Number                            |
| EMIS                 | Emission Measurements in the Automotive Sector | RDE | Real Drive Emissions                          |
| EPA                  | Environment Protection Agency | RSD   | Remote Sensing Devices                        |
| FIA Foundation       | Foundation for the Automobile and Society | SCR | Selective Catalytic Reduction                 |
| FC                   | Fuel Consumption               | SDPFs | DPFs with SCR coating                         |
| GDI                  | Gasoline Direct Injection engine | SEMS | Simplified Emissions Measurement System       |
| GFEI                 | Global Fuel Economy Initiative | SI    | Spark Ignition engine                         |
| GHG                  | Greenhouse Gas                 | TA    | Type Approval                                 |
| GTR15                | Global Technical Regulation No. 15 | TWC | Three-Way Catalyst                           |
| ICEs                 | Internal Combustion Engines    | UN ECE GRPE | the Working Party on Pollution and Energy of United Nations Economic Commission for Europe |
| ITS                  | International Transport Forum  | UNEP  | United Nations Environment Program            |
| LDVs                 | Light Duty Vehicles            | US FTP-75 | United States Federal Test Procedure       |
| LNT                  | Lean NOx Trap                  | US FTP-75 | Worldwide harmonized Light vehicles Test Cycle |
| MTE                  | Mild Term Evaluation           | WLTC  | Worldwide harmonized Light vehicles Test Procedures |
| NEDC                 | New European Driving Cycle     | WLTP  | Worldwide harmonized Light vehicles Test Procedures |
References

[1] Maggiore, M, Road Transport Decarbonisation in the European Research Perspective. Conference Proceedings of “CO2 reduction for Transportation System” June 29-30, Politecnico Torino, Italy.

[2] Bielaczyc P, 2017 Global Powertrain Trends for LDV in Light of Accelerating Changes in Emission Rules and Test Methods. VII International Congress of Combustion Engines PTSS, Poznan, 27-29th June 2017.

[3] ICCT: 2020-2030 CO2 standards for new cars and light-commercial vehicles in the European Union, October 2017, www.theicct.org

[4] Bielaczyc, P, 2016 Which strategy is better for emissions control – the EU or the US?: and introduction to the question. CE-2016-301, Proceedings of the 5th International Exhaust Emissions Symposium 19-20 May 2016, BOSMAL, Bielsko-Biala (Poland), ISBN No. 978-83-931383-9-5.

[5] Bielaczyc, P, 2016 Woodburn, J., Gandyk, M. Trends in automotive emissions, fuels, lubricants, legislation and test methods – a global view, with a focus on the EU & US – Summary of the 5th International Exhaust Emissions Symposium (IEES). Combustion Engines., 166(3), 76-82. doi:10.19206/CE-2016-342.

[6] European Commission: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL setting emission performance standards for new passenger cars and for new light commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from light-duty vehicles and amending Regulation (EC) No 715/2007, Brussels, 8.11.2017 COM(2017) 676 final 2017/0293 (COD)

[7] Tsiakmakis S, Ciuffo B, Fontaras G, Cubito C, Pavlovic J, Anagnostopoulos K, 2017 From NEDC to WLTP: effect on the type-approval CO2 emissions of light-duty vehicles, EUR 28724 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-71642-3, doi:10.2760/93419, JRC107662.

[8] Obama B, 2017 The irreversible momentum of clean energy Science 10.1126/science.aam6284

[9] Engeljehringer K, 2017 Emission regulation and development - from evolution to a paradigm shift (PTNSS-2017-D17), VII International Congress on Combustion Engines PTSS, Poznan, 27th-29th June 2017.

[10] Bielaczyc P, Woodburn J, 2016 Current directions in LD powertrain technology in response to stringent exhaust emissions and fuel efficiency requirements. Combustion Engines., 166 (3), 62-75. doi:10.19206/CE-2016-341.

[11] United Nations ECE: Proposal for Amendment 3 to GTR No. 15 (WLTP), ECE/Trans/WP.29/GRPE/2017/9.

[12] Merkisz J, Pielecha J, Bielaczyc P, and Woodburn J, 2016 "Analysis of Emission Factors in RDE Tests As Well as in NEDC and WLTC Chassis Dynamometer Tests," SAE Technical Paper 2016-01-0980, doi:10.4271/2016-01-0980.

[13] ICCT: Real-Driving emissions test procedure for exhaust gas pollutant emissions of cars and light commercial vehicles in Europe. January 2017.

[14] http://www.europarl.europa.eu/committees/pl/emis/home.html European Parliament (2014-2019), Committee of Inquiry into Emission Measurements in the Automotive Sector, DRAFT REPORT on the inquiry into emission measurements in the automotive sector (2016/2215(INI)), 5.12.2016.

[15] Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008

[16] Commission Regulation (EU) 2017/1151 of 1 June 2017, Official Journal of the EU L175, 7.07.2017 with correction in Commission Regulation 2017/1347 of 13 July 2017, OJ of the EU L 192/1, 24.07.2017.

[17] Commission Regulation (EU) 2017/1154 of 7 June 2017, Official Journal of the EU L175/708, 7.07.2017.
[18] Olechiw M, 2016 USEPA Light-duty Greenhouse Gas Emission Programs and Midterm Evaluation. 37th International Vienna Motor Symposium 28-29 April 2016.
[19] Johnson T, Joshi A, 2017 “Review of Vehicle Engine Efficiency and Emissions,” SAE Technical Paper 2017-01-0907, doi:10.4271/2017-01-0907.
[20] Hill L, 2017 General Legislation Update, 16th August 2017. @2017 Horiba Ltd.
[21] Johnson T, 2017 Vehicular Emissions in Review (PTNSS-2017-D06), VII International Congress on Combustion Engines PTNSS, Poznan, 27th-29th June 2017.
[22] EUROPEAN COMMISSION: COMMISSION NOTICE of 26.1.2017 Guidance on the evaluation of Auxiliary Emission Strategies and the presence of Defeat Devices with regard to the application of Regulation (EC) No 715/2007 on type approvalof motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6), Brussels, 26.1.2017 C(2017) 352 final.