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Impact of the Proposed Euro 7 Regulations on Exhaust Aftertreatment System Design

New Euro standards of global importance to the automotive industry

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Introduction

European emission standards to control air pollution from new motor vehicles were first introduced in 1992 and have been regularly updated and tightened over the past thirty years. They have resulted in significant improvements in air quality and have been used as a blueprint for other regions around the world. Indeed, including their use in major automotive markets such as China and India, nearly 70% of global light-duty and heavy-duty vehicle sales are currently regulated by versions of the European standards or rules closely related to them. Therefore, the introduction of a new set of Euro standards is of global importance to the automotive industry.

In November 2022 the European Commission proposed new Euro 7 standards to reduce pollutant emissions from vehicles and improve air quality (1). Their stated aims were to ensure cleaner vehicles on the road and improved air quality, protecting the health of citizens and the environment. The proposal included measures to ensure that cars, vans, lorries and buses are much cleaner in real driving conditions that better reflect the urban situation where air pollution concerns are the greatest, and that vehicles meet the requirements for longer. It also simplifies the regulations and addresses emissions from brakes and tyres as well as from the tailpipe. Discussions are now underway between the European Parliament, Council and Commission to reach the final Euro 7 agreement.

This review will assess the likely implications of the proposed Euro 7 legislation on the design of exhaust aftertreatment systems for light-duty gasoline, light-duty diesel and heavy-duty diesel applications, in comparison to current Euro 6/VI systems and typical next-generation architectures that were being discussed in response to the development of the Euro 7 proposal.

Euro 6 Catalyst Systems for Light-Duty Vehicles

The Euro 6 light-duty regulations were introduced from 2015 and included a significant tightening of nitrogen oxides (NOx) limits for diesel, which led to the widespread introduction of selective catalytic reduction (SCR) and SCR-coated filter (SCRF) technology, as well as the introduction of gasoline particulate number (PN) limits, which led to the fitment of gasoline particulate filters (GPFs). An arguably more significant change was the subsequent introduction of real driving emissions (RDE) regulations in 2017, which required improved control of tailpipe emissions over a wide range of driving conditions (including urban, rural and highway driving over a range of temperatures and altitudes, allowing for variability in traffic conditions, gradients and weather conditions) rather than over a controlled test under laboratory conditions. The RDE requirements led to improved engine calibrations and control systems, often coupled with modifications to catalyst system design such as additional three-way catalysts (TWCs) or SCR catalysts to control high speed NOx.

The European Commission had stated an ambition to continuously tighten the RDE conformity factors (CFs), the ratios between the allowed emissions in an RDE test and the legislative limit in the laboratory test. Following a long legal challenge on the validity of the use of CFs, Euro 6e limits have been set which tighten the NOx and PN CFs to 1.1 and 1.34, respectively, recognising the error margins of the portable emissions measurement system (PEMS) used to measure real world emissions. These will be introduced from 1st September 2023 for new type approvals and from 1st September 2024 for all new vehicles. The state-of-the-art emissions systems implemented by many original equipment manufacturers (OEMs) to meet the Euro 6d RDE standards are considered capable of meeting the Euro 6e limits and Euro 6e is not expected to lead to significant changes across the fleet. Indeed, many current aftertreatment systems were designed to meet anticipated CFs of one. However, there are likely to be modifications on some applications with borderline emissions, for example vehicles with higher gross weights or where the catalyst system has lower than average engine swept volume or precious metal content.

A typical Euro 6 gasoline aftertreatment system on a new European passenger car (**Figure 1(a)**) comprises one or more advanced TWCs to control the gaseous hydrocarbon, carbon monoxide and NOx pollutants, plus a GPF to control PN emissions. There is a mixture of coated and uncoated GPF systems on the market. Use of a coated GPF gives additional control of gaseous pollutants, especially high-speed NOx emissions, but is seen by some to introduce an unacceptable level of backpressure increase and variability into the system. Use of an uncoated GPF gives lower and more predictable backpressure but often requires additional flowthrough TWC volume to meet the gaseous pollution limits.

A typical Euro 6 light-duty diesel aftertreatment system on a new European passenger car (**Figure 1(b)**) comprises a diesel oxidation catalyst (DOC), followed by either an SCRF or catalysed soot filter (CSF) to control particulate emissions, plus significant downstream SCR catalyst volume. Urea injection is required to generate ammonia for the SCR reaction, and in some SCRF systems dual urea injection is employed in front of both the SCRF and the downstream SCR components to maximise system efficiency in RDE conditions by promoting NOx conversion where the temperature window is more favourable. Copper SCR(F) systems are most common, with engine calibration and oxidation catalysts designed to deliver an NO:NO_2 ratio close to 50:50 to maximise NOx conversion, although some iron SCR catalysts are also used. Systems also often include an ammonia slip catalyst (ASC) function at the rear to enable urea injection levels to be set to deliver optimal NOx conversion while also ensuring minimal ammonia and NOx slip from the tailpipe.

Alternative Euro 6 light-duty diesel systems based on lean NOx trap (LNT) technology were also launched in 2015. LNTs stored NOx during the normal lean operation of a diesel engine *via* oxidation to nitrogen dioxide over a precious metal catalyst and subsequent capture as a nitrate on a storage component such as barium. The technology required regular and periodic rich operation to desorb the trapped NOx and reduce it to nitrogen over a separate rhodium-based catalyst layer. Such systems were favoured on smaller diesel vehicles, where the installation of a urea tank and injection system were problematic. However, they were largely phased out with the introduction of RDE, due to the difficulty of ensuring regular and efficient regeneration in variable real world driving and their inherently lower NOx conversion efficiency during high-speed driving.

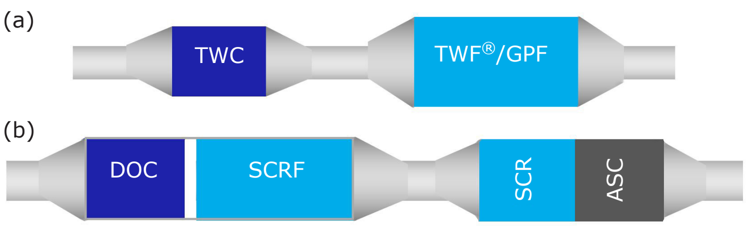

Fig. 1. Schematics of typical Euro 6 light-duty: (a) gasoline; and (b) diesel catalyst systems (not to scale)

Euro VI Catalyst Systems for Heavy-Duty Vehicles

The Euro VI emissions standards for heavy-duty vehicles came into effect from 2013 and required a significant reduction in emissions from the Euro V limits, achieving a stringency comparable to the US2010 standards. For testing over the World Harmonised Transient Cycle (WHTC) NOx limits reduced to 460 mg kWh^{-1}, hydrocarbon limits reduced to 160 mg kWh^{-1} and particulate mass (PM) limits reduced to 10 mg kWh^{-1}. The Euro VI standards also introduced a new PN limit of 6×10^{11} kWh^{-1} as well as stricter OBD requirements, off-cycle and in-use PEMS testing.

A typical Euro VI heavy-duty diesel aftertreatment system (**Figure 2**) comprises a DOC and a CSF, followed by urea injection ahead of multiple SCR and ASC catalysts. A wider range of SCR technologies are employed, with vanadium technologies as well as copper and iron-based catalysts. Vanadium SCR can be used on heavy-duty applications because of the lower operating temperatures, and as it is less reliant on the NO_2:NOx ratio for good NOx conversion can be used in conjunction with DOCs with lower precious metal loading in a more cost-efficient system (2).

Summary of Proposed Euro 7 Regulations

It is widely recognised that the introduction of RDE regulations has resulted in a significant improvement in tailpipe emissions from new light-duty vehicles. Indeed, some commentators have suggested that to continue to improve air quality it is more important to eliminate older internal combustion engine powered vehicles from the general fleet and increase the proportion designed to meet RDE limits than it is to set lower emissions limits for future generations of vehicles. Nevertheless, the European Commission has been developing for several years a proposal for a further tightening of the emissions legislation. Drivers included further improvements to air quality, a simplification of regulations across different types of powertrains and different fuels and control of pollutants not included in previous regulations. As Net Zero ambitions were hardened, it increasingly became viewed as the final step in European emissions regulations before the transition to zero emissions vehicles, especially in light-duty. Inputs were requested from environmental, industry and academic stakeholders, including a programme delivered by the Consortium for ultra-Low Vehicle Emissions (CLOVE) to recommend two scenarios, one with limits achievable with today's best available technology and a stretch target assuming further technology improvements in time for implementation.

Fig. 2. Schematic of typical Euro VI heavy-duty diesel catalyst system (not to scale)

The proposed Euro 7 regulations were finally published by the EU Commission on 10th November 2022. Following a period of feedback, the Commission will present the proposal to the EU Parliament and EU Council. Trialogues will be held between the Parliament, Council and Commission to reach the final agreement.

The Euro 7 proposal for light-duty vehicles is expected to come into force from 1st July 2025. To simplify the regulations there are common limits for gasoline and diesel vehicles for the first time. However, the proposal is not as ambitious as many expected, and limits for the key gaseous pollutants are effectively harmonised at the lower of the gasoline and diesel limits for Euro 6. Therefore, NOx emissions are set at 60 mg km^{-1}, representing a 25% reduction for diesel vehicles and no change for gasoline vehicles. CO emissions are set at 500 mg km^{-1}, representing a 50% reduction for gasoline vehicles and no change for diesel vehicles. Total hydrocarbon (THC) and non-methane hydrocarbon (NMHC) emissions limits are set at the previous gasoline limits of 100 mg km^{-1} and 68 mg km^{-1} respectively; this is the first time a specific hydrocarbon limit has been set for light-duty diesel vehicles.

PN emissions are held at 6×10^{11} km^{-1}, but with the particle size cut-off reduced from 23 nm to 10 nm reflecting the increased confidence in PN measurement capability. Therefore, the effective filtration efficiency required has increased as a greater number of particles are included in the measurements. The particle mass limit is unchanged at 4.5 mg km^{-1}, but vehicles which meet the PN limit generally also comply with the particle mass limit.

A new ammonia limit of 20 mg km^{-1} is included, which will impact both urea injection strategies on diesel vehicles with SCR systems and the extent of rich engine calibrations on gasoline vehicles. However, no limit has been set for N_2O emissions, which would have caused further challenges in optimisation of catalyst chemistry and system design.

RDE are embedded in the Euro 7 proposal and the CF is reduced to 1, i.e. the same emissions limits apply during a real-world test under 'normal conditions' as in a laboratory test. This effectively sets the RDE test as the key development target for emissions control systems. Furthermore, the RDE test boundaries have been broadened, with the maximum temperature increased from 30ºC to 35ºC for normal conditions. The minimum temperature remains at 0ºC.

The extended RDE conditions include a wider temperature range of –10ºC to 45ºC (from –7ºC to 35ºC in Euro 6d) and a maximum altitude of 1800 m rather than 1300 m. While in extended conditions, the OEM is allowed an 'extended driving allowance' where measured emissions are reduced by a factor of 1.6 during the time when the vehicle is within the extended condition. It is also understood that during an RDE test, only one extended condition is allowed at a time. If the test includes multiple extended conditions (for example driving at low temperature while at high altitude), then the emissions for that time period will be removed from the average.

Durability requirements have increased to 200,000 km and 10 years of age. This doubles the durability requirements for in-service conformance checks compared to Euro 6. In detail this is split between a 'main lifetime' up to 160,000 km or eight years and then an 'additional lifetime' up to 200,000 km or 10 years (whichever comes first). For the additional lifetime there is a durability multiplier of 1.2 for gaseous pollutant emissions.

In contrast to the Euro 7 light-duty proposal, the Euro 7 heavy-duty proposal represents a much more significant reduction in emissions limits and a greater technical challenge. Indeed, the proposal is much more in line with the European Commission's impact assessment and recommendation of the 'medium ambition' setting. The heavy-duty standards are proposed with a later implementation date of 1st July 2027. Limits also apply under RDE conditions, which represents a major challenge to the OEMs. Although the altitude and maximum speed criteria for normal conditions are the same as light-duty the temperature range is wider, starting from a lower minimum value of –7ºC up to the same maximum value of 35ºC.

HDD NOx emissions are to be reduced by 80%, from 460 mg kWh^{-1} to 90 mg kWh^{-1} under warm operation, and PN emissions are to be reduced by two-thirds from 6×10^{11} kWh^{-1} to 2×10^{11} kWh^{-1} in conjunction with a change in the particle size cut-off from 23 nm to 10 nm which again has a greater impact on effective filtration efficiency required as more particles are included in the measurements. There are also significant reductions in carbon monoxide and hydrocarbon limits to 200 mg kWh^{-1} and 50 mg kWh^{-1}, respectively. Controls are also introduced for ammonia, at 65 mg kWh^{-1}, and N_2O, at 100 mg kWh^{-1}.

There is also a significant increase in durability requirements for heavy-duty vehicles, with a main lifetime of 750,000 km or 15 years of age, whichever comes first, and an additional lifetime of up to 875,000 km. This reflects both the longer lifetime of a typical heavy-duty vehicle, and the expectation that heavy-duty fleets will continue to rely on internal combustion engines well beyond the transition of new light-duty vehicles to alternative zero carbon powertrains.

Likely Implications of Euro 7 on Catalyst System Design

For gasoline passenger cars a typical 'high technology' system that was being discussed for the most stringent Euro 7 scenarios featured an electrically heated TWC to ensure cold start light-off, a high filtration efficiency GPF, additional TWC volume to realise low NOx emissions and an ASC to mitigate ammonia emissions during periods of rich running.

Following the release of the Euro 7 proposal a general assessment of likely next generation gasoline systems indicates that it is unlikely that a coated EHC will be required, except in the most challenging applications. It is also likely that most vehicles will not need enhanced particulate filters or ASCs, although these could be required on more demanding applications, for example those with a high ratio of vehicle mass to engine displacement. However, the engine swept volume of TWC (both on dedicated TWC and on coated filter, where used) is likely to be larger than a typical Euro 6d system to ensure good control of carbon monoxide and NOx emissions under RDE conditions. Therefore, compared to Euro 6d architectures many Euro 7 gasoline systems are likely to include an additional downstream TWC component in addition to the close-coupled TWC and GPF (**Figure 3**). At this stage it is not clear that higher platinum group

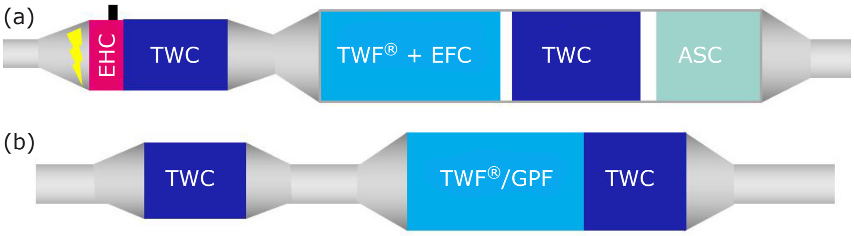

Fig. 3. Schematics of: (a) 'high technology'; and (b) likely mainstream Euro 7 light-duty gasoline catalyst systems (not to scale)

metal (pgm) concentrations will be required to meet Euro 7 targets, but it is possible that there may be a modest increase in total pgm loadings per system as a result of the increased catalyst volume.

For diesel passenger cars a typical 'high technology' system that was being discussed for the most stringent Euro 7 scenarios featured an electrically heated DOC (to meet cold start RDE requirements), close-coupled DOC and a combination of iron and copper SCR catalysts (to provide urban RDE control in cold operating conditions while controlling N_2O formation) upstream of an SCRF with enhanced filtration efficiency, followed by downstream SCR and ASC components.

Following the release of the Euro 7 proposal, a general assessment of likely next generation light-duty diesel systems indicates that a typical system will require close-coupled DOC and SCR catalysts upstream of the SCRF, with downstream SCR and ASC components (**Figure 4**). Electrically heated catalysts will be optional for more challenging applications, with focus on cold start emissions in real world urban driving. Dual urea injection upstream of both the close-coupled SCR/SCRF components and the underfloor SCR/ASC components will be commonly used to maximise NOx conversion under different exhaust temperature profiles. The upstream SCR catalyst will be important to deliver cold start NOx performance, although the absence of an N_2O limit reduces some of the constraints of the choice of SCR coating. High filtration efficiency filters will be required to deal with urea-derived PN emissions, especially on heavier vehicles such as vans. The volume of downstream SCR and ASC components is also expected to be larger than a typical Euro 6 system in order to ensure RDE compliance for NOx.

As the Euro 7 emissions challenge for heavy-duty applications is significantly greater than for light-duty, both in terms of tailpipe emissions and durability, the typical next generation heavy-duty diesel aftertreatment system is likely to be more complex than current systems. Most will include close-coupled urea injection and a close-coupled SCR catalyst, in order to achieve rapid light-off of NOx conversion and control NOx emissions at start-up and in cold operating conditions where the traditional downstream SCR catalysts are not in the required operating temperature window. This will sit upstream of a DOC, which will function as an ASC for the close-coupled SCR catalyst as well as its traditional role in converting carbon monoxide and hydrocarbon emissions. The CSF is likely to require an enhanced coating to deliver improved filtration efficiency and meet the lower PN standard without giving a significant backpressure penalty. Following a second urea injection point there will be an array of SCR and ASC catalysts, probably with greater volume than a typical Euro VI system, and as with Euro VI the market is likely to see a mixture of copper, iron and vanadium catalysts although the N_2O limit may favour greater uptake of vanadium technology.

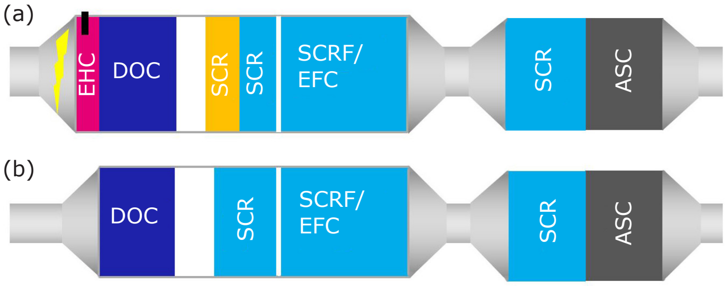

Fig. 4. Schematics of: (a) 'high technology'; and (b) likely mainstream Euro 7 light-duty diesel catalyst systems (not to scale)

In some cases, an additional DOC may be incorporated close to the exhaust manifold, possibly with electrical heating, to generate an exotherm to ensure that exhaust gas temperatures are high enough for effective decomposition of urea to generate ammonia and to enable high levels of NOx conversion over the close-coupled SCR catalyst (**Figure 5**).

Next Steps

There has been a broad spectrum of reactions to the Euro 7 proposals. For light-duty applications representatives of the vehicle manufacturers have commented that complying to the new limits would add significant constraints to the automotive industry and add to the price of new vehicles and that the investment required would be better utilised focusing on making electric vehicles more affordable and developing more zero-emission technologies to improve the vehicle fleet (3). In contrast, environmental groups were disappointed that the final emissions step was not more stringent and others have called for swift adoption of ambitious emissions targets in order to maximise the benefit during the remaining years of sale of internal combustion engines (4).

For heavy-duty it is recognised that the proposal is more challenging, reflecting the general belief that the lifetime of the internal combustion engine in heavy-duty vehicles is likely to be longer than for passenger cars and it is therefore more important to ensure that a standard is set which continues to control emissions from the fleet well into the future. Therefore, there have been fewer public statements made about the appropriateness of the proposed heavy-duty limits.

As further stakeholder feedback is considered by the EU Parliament and Member States (EU Council) it is likely to lead to both Parliament and Council taking positions on the proposal and seeking amendments during the co-legislative process. It is, therefore, expected to be 12 to 18 months from publication before the final regulations are confirmed and implemented in legislation, which is causing concern in the automotive industry about the time available to introduce Euro 7 compliant vehicles, especially to comply with the light-duty launch date of 1st July 2025.

Conclusions

The Euro 7 proposal has succeeded in providing a simplified framework for emissions legislation compared to previous generations and, in shifting the emphasis from testing in a laboratory under controlled conditions to real-world emissions testing, has increased the relevance of the proposed emissions limits to the pollution levels experienced by citizens, especially in urban environments. For heavy-duty vehicles the step change from Euro VI is significant and will drive major changes in aftertreatment technology, giving benefits over the expected longer lifetimes of these applications. In contrast the light-duty proposals are less ambitious and will result in smaller changes compared to Euro 6e applications, especially for gasoline engines.

The Euro 7 systems described above are a generic description of typical systems, based upon the authors' knowledge of designs being developed in anticipation of the proposed Euro 7 limits and an initial assessment of how the proposals are likely to affect those assumptions. It is important to note that in practice a wide range of catalyst and system choices will be made by the vehicle manufacturers according to a variety of factors including vehicle characteristics, engine out emissions, catalyst operating temperatures, system cost, previous assumptions made about likely Euro 7 emissions limits and the resource or time available to further optimise current development systems.

At the time of writing discussions continue towards the final agreement of the Euro 7 emissions standards. Emissions control system designs will inevitably evolve as manufacturers take stock of the proposed Euro 7 limits, the confirmed legislation and the implications for their specific applications and as further improvements in catalyst technology are adopted into the market. It is, therefore, the intention of the authors to follow up with a more detailed review of Euro 7 emissions control systems once the legislation has been confirmed and the impact on production intent designs is better understood.

Fig. 5. Schematic of a likely example Euro 7 heavy-duty diesel catalyst system (not to scale)

Glossary

ASC	ammonia slip catalyst
CF	conformity factor
CSF	catalysed soot filter
DOC	diesel oxidation catalyst
EFC	enhanced filtration coating
EHC	electrically heated catalyst
GPF	gasoline particulate filter
LNT	lean NOx trap
NMHC	non-methane hydrocarbon
NOx	nitrogen oxides
OBD	on-board diagnostics
OEM	original equipment manufacturer
PEMS	portable emissions measurement system
PM	particulate mass
PN	particulate number
RDE	real driving emissions
SCR	selective catalytic reduction
SCRF	SCR-coated filter
THC	total hydrocarbon
TWC	three-way catalyst
TWF®	Three Way Filter®
WHTC	World Harmonised Transient Cycle

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Authors' Note

For previous generations of European legislation, the convention has been that the European light-duty and heavy-duty regulations have been described using Arabic and Roman numerals, respectively: for example, Euro 6 for light-duty and Euro VI for heavy-duty. The European Commission has presented the Euro 7 proposal as a combined package and in this review we have used Euro 7 light-duty and Euro 7 heavy-duty to differentiate between the subsets of regulations. However, the term Euro VII is also used commonly in the industry and should be considered as interchangeable with Euro 7 heavy-duty.

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