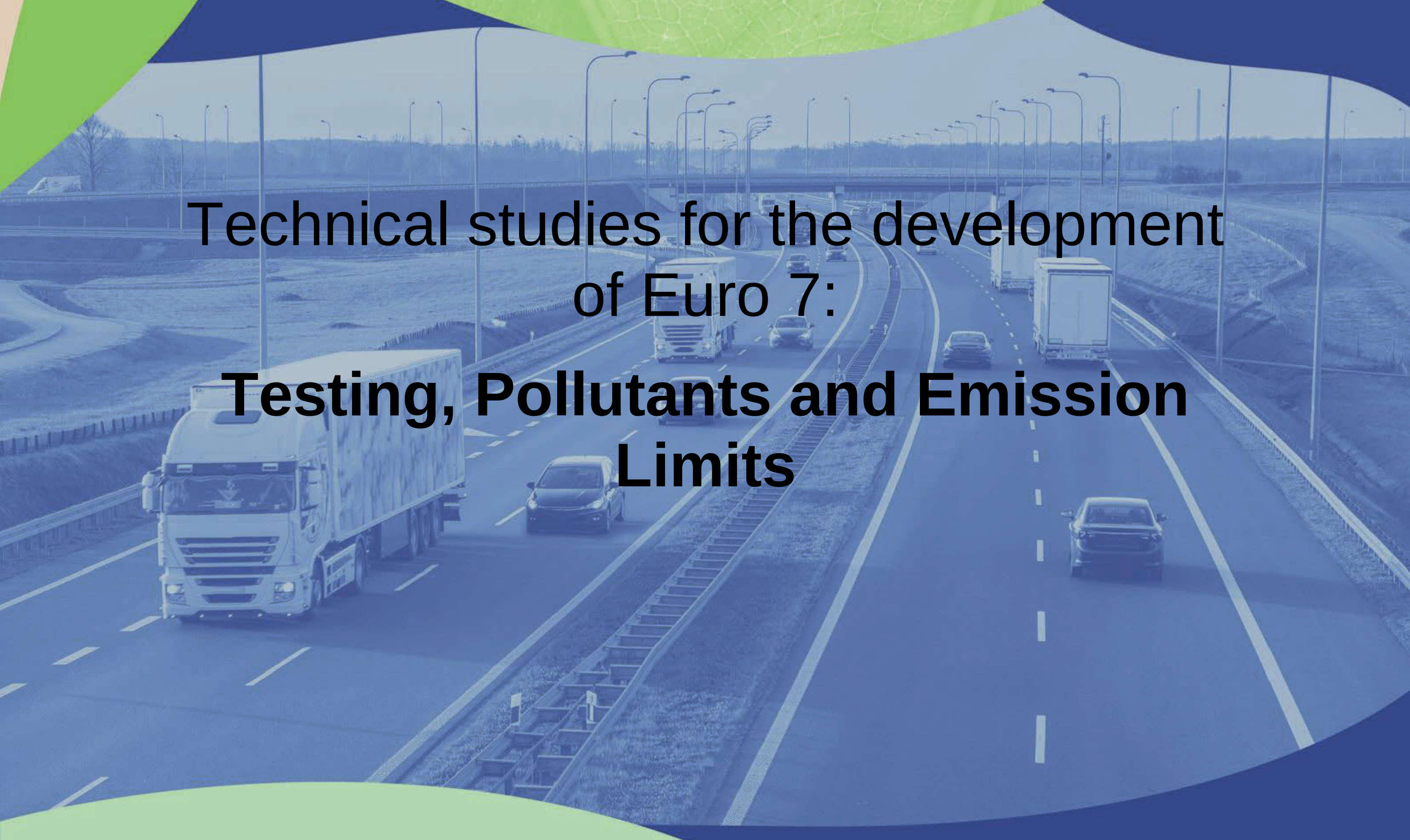
Euro 7 Vehicle emission standards: A European Green Deal proposal



Technical studies for the development of Euro 7:

Testing, Pollutants and Emission Limits

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Executive Summary

This report is a deliverable under the framework "Study on post-EURO 6/VI emission standards in Europe". The overall study aims to provide the European Commission (EC) with the technical background required to design a comprehensive regulatory package for the emission control of motor vehicles in the EU.

Emission species recommended to be covered in the EURO 7 legislation were evaluated by considering their health and environmental impacts and potential presence in vehicle exhaust when using different engines, exhaust emission control and fuels. A wide array of emission species were evaluated based on air quality regulations, health risk classifications and literature. In parallel, emission standards outside of the EU were taken into account. Recommendations to measure and set emission limits for the emission species were then evaluated based on the capabilities of measurement technologies to be used in on-road testing.

The emission species recommended to be covered in EURO 7 (in addition to those already regulated in Euro 6/VI) are NO_x, CO, SPN (nominally >10nm), PM, NH_3, N_2O, CH_4, HCHO, NMOG and brake wear (PM & Total PN) emissions. The majority of emission species are recommended to be measured and limited on-road, with the exception of PM and NMOG (THC is needed for calculating NMOG), which are recommended to be primarily measured in-laboratory until suitable portable emissions measurement system (PEMS) technologies have been developed for on-road testing.

As part of this study, a database was developed with test data from the latest technology vehicles to identify the current best performing light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) within and beyond current testing conditions. Analysis of these vehicles also served to identify critical operating conditions that are associated with emissions excursions, which informed the recommendations for testing conditions under EURO 7. The database includes measurement data from CLOVE partners (both from testing activity within the current framework contract and from own data) as well as from the JRC and other stakeholders. All fuel types are covered i.e., diesel, petrol, compressed natural gas (CNG), liquefied petroleum gas (LPG) and hybrid-electric vehicles, while a wide range of different components and configurations regarding emission control systems are included, covering almost all the main configurations observed in the latest technology vehicles. Testing of these vehicles covered a wide variety of on-road (e.g., RDE-compliant tests, dynamic driving, short trips etc.) and chassis dynamometer tests (e.g., WLTC, TFL, RDE replication etc.). Emissions data for these vehicles and tests include the currently regulated emissions species (i.e., CO, CO_2, NO_x and SPN_{23} for RDE tests) and in the case of chassis dynamometer tests also the currently non-regulated emissions species (e.g., CH_4, N_2O, NH_3).

Assessment of the test results for LDVs indicates that almost all test vehicles comply with the current Euro 6 limits, when tested within the current RDE test boundaries, regardless of their powertrain, emissions control technology, or size. Much higher emission levels were detected when testing was conducted within the broader RDE conditions considered for EURO 7. This trend is observed in both the regulated and the (currently) non-regulated emissions. The deficiencies and the remaining issues observed can be summarised as follows:

1. Cold start – short trips
2. Low ambient temperature
3. High engine power events/periods, including (i) harsh accelerations, (ii) uphill driving, high vehicle payload and/or trailer towing, and (iii) high vehicle speed
4. Idling and low load driving which may occur during traffic congestion (severe stop-and-go situations)

5. DPF regeneration and when filter is clean
6. High SPN from technologies currently not included in regulation (PFI and NG)

In the case of HDVs, although the average emission levels of HDVs dropped significantly with Euro VI, several open issues remain whereby some relevant real-world situations are not well covered by the regulations. The assessment of the test results for HDVs indicates that these are:

1. Low load driving situations
2. Coverage of emissions over real vehicle lifetime
3. Detection of malfunctions in real driving conditions
4. Coverage of cold start emissions

In addition, specific shortcomings of Euro VI relevant to HDVs relate to the way the emissions in the moving average windows (MAWs) are evaluated today. PEMS tests are currently evaluated based on MAWs driven with an average power of more than 10% of the rated power and a size defined by the WHTC work or CO_2 emissions. The 10 percentiles of the MAWs with the highest emissions are then omitted in the evaluation.

Based on these findings, the **testing conditions** examined and recommended for EURO 7 aim to address these areas for improvement and the pollutants recommended for inclusion under the new standard. The recommended testing conditions for EURO 7 are intended to further increase the coverage of all normal usages of vehicles, including the edges of normal use for both LDV and HDV, where high emissions may occur. Boundaries for which there is little evidence that vehicles cannot perform well, and those where vehicles have shown to have little problem, are recommended to be removed or extended to extend the coverage of all “normal” European driving. Moreover, other normal, yet more rare, operations are recommended to be included under additional “extended” testing conditions, with higher limits.

Regarding the **“normal” conditions,** in many cases the extreme boundary under the current RDE legislation (RDE4), with the factor 1.6 applied, is carried over. The minimum distance is therefore 16 kilometres (from urban evaluation), the temperature is set at the range -7 °C to 35 °C. Maximum altitude is increased from 1300 metres to 1600 metres, since little evidence exists to demonstrate that altitude is a fundamental or technical problem for emission control technologies. For the same reason, the maximum velocity is increased from 145 km/h to 160 km/h.

A single new boundary condition is introduced, related to the worst-case test conditions and execution. Since the cold start is aggravated at low ambient temperatures and high engine loads, the engine power in the normal conditions is restricted during the first two kilometres. The analysis conducted indicates starts last at most up to two kilometres but can be much shorter. So, for any time interval from the start until the first two kilometres are covered the average power should remain below 20% of the rated power. In the extended test regime this restriction is lifted and high engine loads at the cold start are also covered in this case with a higher associated limit.

The recommendation for the new **“extended” conditions** is an extension to cover all of European usages and conditions. The associated limits are altitudes up to 2200 metres, typical of high Alpine passes; and the -10 °C to 45 °C temperature range, incorporating high temperatures observed regularly in the summer. The low temperatures have been raised as an issue of an aggravating factor in the worst-case, cold start test. The increases in the cold start emissions, with lower temperatures led to a slightly moderate extended condition down to -10 °C. The remaining boundaries are not a large deviation from current RDE in normal conditions, except for the maximal mileage which is raised from 100 000 km/5 years to 240 000 km/15 years, to reflect the normal useful life of modern vehicles.

In addition to these recommendations for EURO 7 testing for LDVs, features unique to HDVs were considered - including variability in HDV applications and manufacturing processes - before testing recommendations for HDVs were recommended. The engine test procedure outlined in Regulation EU 2017/2400, which defines the test conditions for CO_2 emission declaration, also includes pollutant emissions measurement. Unless the CO_2 determination methods are amended, it is recommended that these test procedures should be maintained in EURO 7.

Taking into consideration the pollutants recommended for inclusion and the input collected during the stakeholder consultations conducted as part of this study, comprehensive technology tables were developed with a number of potential future technology packages for the different powertrains (diesel/petrol/CNG/LPG for cars and vans, diesel/CNG for lorries and buses). After selecting the potential future technology packages their emission reduction potential was evaluated, using:

1. Simulations of the emission performance of technology packages, using tools and software available within the CLOVE partners.
2. Emissions data collected during the consultations and retrieved from literature, including prototypes developed in European research projects.
3. Test data from demonstrator vehicles integrating future technology packages, provided by stakeholders.

The evaluation of the emission reduction potential of the technology packages focused particularly on driving conditions characterised by emissions excursions. In total, eighteen LDV and seven HDV EURO 7 technology packages were evaluated with different fuel and engine concepts and varying complexity of exhaust gas emission control. The hardware costs associated with these EURO 7 technology packages were also calculated as incremental cost to the latest Euro 6/VI technologies. This analysis covers only the hardware costs, while other cost categories (e.g., R&D costs) are considered in the Impact Assessment study.

Based on the analysis conducted, CLOVE recommends the introduction of a two-area form of limit. Under this two-area form of limit, a constant limit value in mg (or particles for PN emissions), referred to as “budget”, is applied up to a reference distance of 16 km (a reference distance of 10 km is also briefly discussed in this report as an alternative), while a constant limit in mg/km (or p/km for PN emissions) is applied for trips above 16 km. The budget is calculated from the mg/km value applied to the same pollutant and enables “one single limit” to be applied to light-duty testing.

The recommended limits for cars and vans under EURO 7 are presented in Table 0-1.

These limits assume measurement uncertainties of 15% for gases and 40% for PN_{10}. Nevertheless, similar to the case of HDVs, this margin could be excluded if all tests which are around the limit within the analyser tolerances are repeated with a reasonable statistical approach. PN_{10} limits include the incremental conversion factor from 23 nm to 10 nm. These limits apply to those trips that fall within the recommended testing and evaluation boundaries for “normal” driving conditions. For LCVs, it is recommended that a multiplier of x1.5 is applied for CO, NOx, and N_2O compared to the respective limits of passenger cars (HCHO limits are two times higher). This multiplier is derived from the ratio of current Euro 6 limits in N1-Class III compared to M1 and takes into account the expected technology improvement in EURO 7 technologies. No extra allowance is applied in the case of NMOG, NH_3, CH_4, and PM, PN emissions, as it is expected that EURO 7 technologies will be able to control emission levels of these species.

Table 0-1

Recommended emission limits for cars and vans under normal conditions for Scenarios 1 and 2

Pollutant	CO	NMOG	NOx	PM	SPN10	NH3	CH4	N2O	HCHO
Unit	mg/km	mg/km	mg/km	mg/km	#/km	mg/km	mg/km	mg/km	mg/km
Scenario 1									
Cars and Vans	400	45	30	2	1×1011	10	20	20	5
Vans with TPMLM>2500 kg & PWR<35 kW/t	600	45	45	2	1×1011	10	20	30	10
Scenario 2									
Cars and Vans	400	25	20	2	1×10^{11}	10	10	10	5
Vans with TPMLM>2500 kg & PWR<35 kW/t	600	25	30	2	1×10^{11}	10	10	15	10

These limits assume measurement uncertainties of 15% for gases and 40% for PN_{10}. Nevertheless, similar to the case of HDVs, this margin could be excluded if all tests which are around the limit within the analyser tolerances are repeated with a reasonable statistical approach. PN_{10} limits include the incremental conversion factor from 23 nm to 10 nm. These limits apply to those trips that fall within the recommended testing and evaluation boundaries for “normal” driving conditions. For LCVs, it is recommended that a multiplier of x1.5 is applied for CO, NOx, and N_2O compared to the respective limits of passenger cars (HCHO limits are two times higher). This multiplier is derived from the ratio of current Euro 6 limits in N1-Class III compared to M1 and takes into account the expected technology improvement in EURO 7 technologies. No extra allowance is applied in the case of NMOG, NH_3, CH_4, and PM, PN emissions, as it is expected that EURO 7 technologies will be able to control emission levels of these species.

Under “extended conditions” of use, an emission limit multiplier of ×3 is recommended to be applied. Regarding durability requirements, the recommended limit values correspond to 160k km and 8 years. Further deterioration factors will be applied up to 240k km. These factors will be determined by an on-going parallel project.

For HDVs, the same two-area form of limit is also recommended. Different limits for hot and for cold driving conditions are recommended for EURO 7. The corresponding limit regime is designed as follows:

- The cold phase and the beginning of hot conditions are limited by a "budget", which defines the maximum emissions allowed for a test up to an engine work of 3 x WHTC. This budget is defined by a corresponding limit $[mg/kWh]_{Budget}$ and the kWh work the tested engine delivers in 3xWHTC. Any test up to 3xWHTC work has to be below the resulting limit in [mg/test].
- The hot emissions are limited by a separate $[mg/kWh]_{hot}$ limit, which has to be met under hot conditions.
- To safeguard the MAWs not covered by the possible 90th percentile approach, a "100th percentile" limit is added, which must not be exceeded in any MAW between 1st and last second of a test.

Table 0-2

Limits for the two EURO 7 technologies for EURO VI durability requirements in mg/kWh (#/kWh for PN)

100th Percentile Limits**	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG**	**NH_3**	**N_2O***	**CH_4***
H2 (EURO 7 w/o pre-heating)	350	5×10^{11}	12	7500	200	70	300	500
H3 (EURO 7+pre-heating)	175	5×10^{11}	12	3000	75	70	300	500
90th Percentile Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG**	**NH_3**	**N_2O***	**CH_4***
H2 (EURO 7 w/o pre-heating)	90	1×10^{11}	8	300	50	70	60	350
H3 (EURO 7+pre-heating)	90	1×10^{11}	8	300	50	70	60	350
Budget Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG**	**NH_3**	**N_2O**	**CH_4**
H2 (EURO 7 w/o pre-heating)	150	2×10^{11}	10	2700	75	70	260	500
H3 (EURO 7+pre-heating)	100	2×10^{11}	10	1200	50	70	260	500

* Limit composition for CH_4 and N_2O results in less than 5% share of CO_2e emissions vs. tailpipe CO_2 in worst-case conditions (average will be lower). Limits applicable to cycle averages, not suggested for each MAW

** For HCHO a limit value of 30 mg/kWh is assumed to be feasible for the H1 and H2 technologies and is in line with the PEMS analyser capabilities. The value should be validated later, since HCHO was not measured in the EURO 7 demonstrator tests and simulation of HCHO was not possible for HDVs.

The hot emissions are limited by a 90th percentile of MAWs and the 100th Percentile limit is applicable over the entire test not only limiting the cold start phase (e.g. for NH_3 highest emissions are expected under hot and high load conditions). With the “budget” method any short test can also be evaluated.

The recommended limits for HDVs are presented in Table 0-2. These are based on single engine concepts and technologies denoted as H2 and H3 respectively. PN_{10} limits include the incremental conversion factor from 23 nm to 10 nm. In all cases, a safety margin is included to consider the margin related to serial spread in production of engine systems and to the worst-case situation/conditions, as further discussed in section 8.3. Finally, as regards the analyser uncertainty, assuming that all tests which are around the limit within the analyser tolerances are repeated with a reasonable statistical approach, no extra margin is needed. Thus, this is not included in the recommended limit values.

Non-exhaust emissions are also considered under this study as these emissions account for a significant and increasing proportion of total vehicle emissions as exhaust emissions decrease. A desk-based review was conducted to assess the potential for further control of **evaporative emissions** during vehicle operation, while stationary, and during refuelling as well as for particle emissions control resulting from brake and tyre wear. The main technologies and measures that can be employed to reduce evaporative emissions include low permeation hoses, low permeation fuel tanks and seals, and the use of larger carbon canisters with higher purge rates. On-board Refuelling Vapour Recovery (ORVR) is considered as a vehicle measure to control emissions that occur during refuelling.

Further recommendations are made to ensure effectiveness of testing procedures and emission limits under demanding operation (short driving events and lengthy driving events at high temperature) and climatic conditions (extended parking events at high temperature). These also include consideration of OBD leakage detection with an appropriate leak detection limit.

For brake and tyre wear, there is currently no legislation in Europe – or any other part of the world – that explicitly regulates these emissions. However, the literature and the targeted consultation identified several technologies with the potential to reduce non-exhaust PM, although their true effectiveness remains uncertain. For tyre wear, technology options include low rolling resistance tyre compounds, subject to proof of benefits, and the adaptation of the tyre air pressure to limit wear, by means of tyre pressure monitoring and regulating. Consistently optimal tyre pressures will minimise tyre wear. For brake wear, technologies to be explored or further developed to enable lower emissions include regenerative braking, improved pad materials, brake wear particulate collection methods, coated discs and others (e.g., brake encapsulation methods). Based on the feasibility and potential of the different technologies and the literature sources collected, specific proposals for future reductions of brake emissions are offered in this report.

On-board diagnostics, on-board measurement and geofencing were also assessed as part of this study. Within the current OBD legislation defined emission relevant subsystems are diagnosed. If a certain subsystem has a malfunction that results in not fulfilling the On-Board Threshold emission Limit (OTL), considering also the In-Use Performance Ratios (IUPR), the malfunction indicator lamp (MiL) must be activated. Nevertheless, specific weak points are detected: depending on the malfunction, emission drawback in RDE can be much higher than in WLTP, superposition of more than one malfunction can lead to high emissions, there are systems/occasions with emission impact that are not monitored within current Euro 6 legislation (e.g., DPF regeneration frequency monitor), pinpointing requirement is challenging for some emission reduction systems, MiL reaction is complicated etc. In such an environment, introducing direct and continuous on-board emission monitoring (OBM) seems to be a promising measure. In general, the OBM system can track emission-related data for each vehicle using physical sensors and calculation models. This data can be available for either on-board or on-the-cloud data processing via the on-board control units (i.e., engine and communication control units).

Two main topics are examined in detail: the technical feasibility of sensors, and the possible policies that can be developed based on OBM data. For both topics, a 2-phase approach (short term and long term) is analysed aiming initially at an early introduction of the already feasible monitoring policies and species and in parallel, at providing enough time for the development of new sensors and techniques to monitor all species for all proposed policies.

As regards emission sensing techniques:

- NOx emissions monitoring can be realised even with the currently available amperometric sensors. Technical constraints will be gradually overcome (e.g., NOx sensors running-in time reduced to 45-60 s), thus, OBM accuracy can be improved.
- NH_3 emission monitoring can be feasible for diesel applications with the market-available mixed-potential sensor and for petrol applications with the utilisation of the NH_3 sensitivity of amperometric NOx sensor in combination with a proper algorithm to distinguish NH_3 and NOx emission. Recently, concerns have been raised for the durability of the sensor and, in particular, its sensitivity to deterioration effects which can lead to poor performance after only a few years of normal operation. Alternative approaches (i.e., composite NOx+NH_3 monitoring) or new sensing technologies could be further examined to fulfil the target for NH_3 monitoring.
- Currently, PM and PN emissions monitoring technologies are not mature. Therefore, the monitoring can start (phase 1) with advanced on-board diagnostics of the diesel particulate filter utilising the resistive sensors to check the vehicle emission conformity. Furthermore, regarding GPF diagnosis, current technology will also be used (oxygen storage capacity (OSC) measurement via lambda sensor, temperature- and pressure-based diagnosis). However, on a next phase, PM and PN monitoring should gradually replace the filter diagnosis with the development of advanced sensor technologies (Electrostatic, Diffusion Charge and Laser Induced Incandescence).
- Finally, there are no currently available sensors for other species apart from NOx, PM/PN and NH_3. The technical solutions for such sensors are considered immature and there is very limited information and data to assess the technical feasibility of such sensors. The possibility to monitor CO/HC/CH_4 emissions was also investigated but the proposed solution (model-based approach) should be further investigated and checked.

The OBM policies are addressed either to individual vehicles or to vehicle types, e.g.:

- Policies for individual vehicles
    - Identification and measures for high emitters (e.g., limp mode, MiL activation): MiL activation if floating average emissions of 10 valid trips (e.g., 5 km each) are above the emissions limit plus OBM tolerance. Further actions are taken (i.e., limiting of vehicle cold start number) if the MiL is still active after 10 trips.
    - Tampering detection: Exploiting OBM system data to detect malevolent tampering. On-board security (e.g., secure communication networks) are prerequisites.
    - Improved roadworthiness inspections: Ultimately, alleviation of other emissions testing procedures like Periodic Technical Inspection (PTI) or Road-Side Inspection (RSI).
    - Long-term evaluation of vehicle's emission performance
- Policies for vehicle types

- ISC emission testing procedures alleviation
- Tampering detection
- ISC and MaS vehicle preselection
- Provide type-based emission compliance and performance monitoring (regardless of boundary and driving conditions)

With a wide range of emission testing, including all normal trips, it is also possible to test vehicles when intelligent vehicle systems, like automated driving and learning emission control, are engaged. This will be an extension from the current RDE, while both the trip and driving requirements excluded some of the cases. However, special attention is required for geofencing as a method to apply zero emission operation. In upcoming zero-emission zones in European cities, the local authorities should be enabled to instigate and enforce such a zero-emission zone, where the combustion engine will remain off. Geofencing must therefore be combined with appropriate reporting and enforcement mechanisms for in-service emissions.

1 Introduction

1.1 Background

This report has been prepared in the framework of the “Study on post-EURO 6/VI emission standards in Europe (hereafter referred to as ‘the project’), aiming at providing the European Commission (EC) with the technical background required to design a comprehensive regulatory package for the emission control of new vehicles in the European Union (EU).

Across Europe, road transport remains the dominant component within the transport sector. This trend is forecast to continue to 2050, with growth of 16% in road passenger transport (expressed in passenger kilometres) between 2010 and 2030, rising to 30% for the period 2010 to 2050. Road freight transport (expressed in tonne kilometres) is also projected to increase by 33% and 55% respectively over the same timeframe (JRC, 2019).

Road transport is considered a key contributor to air pollution, which is the leading environmental cause of premature death in the European Union (EU), responsible for more than 400,000 premature deaths per year (European Environment Agency, 2017; Roderiguez, et al., 2019). According to the World Health Organization (WHO) (2016), exposure to air pollution can cause or aggravate heart and respiratory ailments, such as heart attacks and asthma; can affect the nervous and reproductive systems; and has been linked to occurrences of cancer, stroke, diabetes, and Alzheimer’s disease. NOx emissions from the road transport sector reduced by 63% from 1990 to 2018. However, the transport sector is a major source of the ground-level ozone precursors contributing by 39% to NOx, 20% to CO and 8% to NMVOCs in 2018, in the EU. Transport sector is also a major source of PM emissions (EEA, 2019).

It is for this reason that the European Commission strives to stimulate a market of the best, cleanest and most competitive vehicles to support its zero-pollution ambition for the EU. A key element in addressing this has been the “Euro” vehicle emission standards, first implemented in 1991, with further developments up to Euro 6 and Euro VI for light-duty vehicles (LDV) and heavy-duty vehicles (HDV) respectively. In the years since, there have been amendments to the Euro 6/VI standards associated with changes to emissions testing procedures, with the current emission standards aiming to include more real driving emissions measurements by using portable emission measurement systems (PEMS) tests for pollutants and implementing processes such as the verification testing procedure (VTP), introduced under Commission Regulation (EU) 2017/2400, for CO_2 emissions and fuel consumption to ensure that emissions remain below the limits for a wide range of conditions of use.

The reasoning behind these amendments initially was that early Euro 6/VI standards did not achieve the intended impacts on real-world regulated emissions. Their introduction though, alongside fleet-average CO_2 requirements, drove the wide adoption of disruptive engine and vehicle technologies. These disruptive technologies, for the first time, combined different degrees of electrification and internal combustion engines. In response, developments within the latter steps of the Euro 6/VI standards required the implementation of advanced emission control systems which function efficiently under real-world conditions: a challenge due to the impacts of electrification on thermal characteristics and exhaust gas composition.

Several emissions species that are currently not directly regulated under the Euro standards are found at significant concentrations in ambient air and present significant harmful impacts to health and the environment, in particular nitrogen dioxide (NO_2). Furthermore, the use of emission control technologies such as selective catalytic reduction systems (SCR) and three-way catalysts (TWC) to achieve the emissions limits outlined in Euro 6/VI standards for nitrogen oxides (NOx) have impacted emissions of other pollutants.

1.2 Objectives

The objectives of the project are as follows:

- Perform a technical review of EU standards, with respect to their structure, coverage, and robust implementation. Assess the effectiveness of these standards and identify areas where technical improvements can be made and where robust methods are already in place. Provide recommendations for components of the standards where the testing/overall approach may be improved, abolished or restructured.
- Develop and propose new tests to address inefficiencies of the current testing framework and propose pollutant species to be considered for inclusion in post-Euro 6/VI, hereafter referred to as “EURO 7”. For the purposes of this report, EURO 7 refers to both light and heavy-duty vehicles.
- Perform vehicle testing and analyse test results and existing emissions data, produced by the members of the CLOVE Consortium, the JRC and stakeholders. The target is to highlight areas of the testing regimes where high emissions are observed for a range of applications.
- Collection and assessment of detailed information on the technologies for controlling the relevant emission species identified, their emissions abatement performance and costs. Development of recommendations for possible limit values for the prioritised list of emissions species.

1.3 Structure of this report

The outcomes of the project are summarised in the following sections of this report:

- ***Chapter 2*****:** Outlines the methodological approach undertaken
- ***Chapter 3:*** Outlines the emissions species for inclusion in EURO 7 and minimum recommendable limit values based on PEMS analyser capabilities.
- ***Chapter 4:*** Summarises the evaluation of the technical effectiveness of Euro 6) and presents the findings on tailpipe emissions (LDVs).
- ***Chapter 5:*** Summarises the evaluation of the technical effectiveness of Euro VI and presents the findings on tailpipe emissions (HDVs)
- ***Chapter 6*****:** Outlines the recommended EURO 7 testing conditions.
- ***Chapter 7:*** Proposes EURO 7 limits and outlines technologies to meet them (LDVs).
- ***Chapter 8:*** Proposes EURO 7 limits and outlines technologies to meet them (HDVs).
- ***Chapter 9:*** Presents the findings on evaporative.
- ***Chapter 10:*** Presents the findings on brake and tyre wear emissions.
- ***Chapter 11:*** Presents the findings on On-Board Diagnostics, On-Board Monitoring and Geofencing.
- ***Chapter 12:*** Summarises the final technical recommendations for EURO 7.

This report is accompanied by Annexes (in a separate document), which contain the following:

- **Annex 1:** Provides an overview of the Euro 6/VI emission standards.
- **Annex 2:** Provides supporting evidence regarding vehicle testing by the CLOVE Consortium, the JRC and stakeholders both for LDV and HDV.
- **Annex 3:** Outlines the technoeconomic questions posed to stakeholders as part of the 2nd Targeted stakeholder consultation.
- **Annex 4:** Provides a detailed list of technology packages recommended in the stakeholder consultation and literature.
- **Annex 5:** Provides details for durability coverage over lifetime and detection of malfunctions of HDV.

Some of the outcomes described in this report feed into the impact assessment study.

2 Methodology

To achieve the objective of developing technology scenarios and respective emissions performance and suggested limits to be further evaluated in the impact assessment study, the methodology that has been followed comprises five steps as illustrated in Figure 2-1 and explained below the Figure.

1. **Step 1:** Development of an emissions database with performance of latest technology vehicles within and beyond current testing boundaries (described in Chapters 4 & 5, accompanied by the Annexes)
2. **Step 2:** Emissions performance evaluation using the CLOVE database and identification of critical operating conditions that are associated with emissions excursions (analysed in Chapters 4 & 5)
3. **Step 3:** Identification of future technology packages to be further evaluated in terms of emissions performance and cost (analysed in Chapters 7 & 8)
4. **Step 4:** Evaluation of emission reduction potential of future technology packages (selected in Step 3), under specified operating conditions and cost estimates (analysed in Chapters 7 & 8)
5. **Step 5:** Recommendation of emission limits, technology scenarios and costs to be included in the cost-benefit analysis of the impact assessment study (analysed in Chapters 7 & 8)

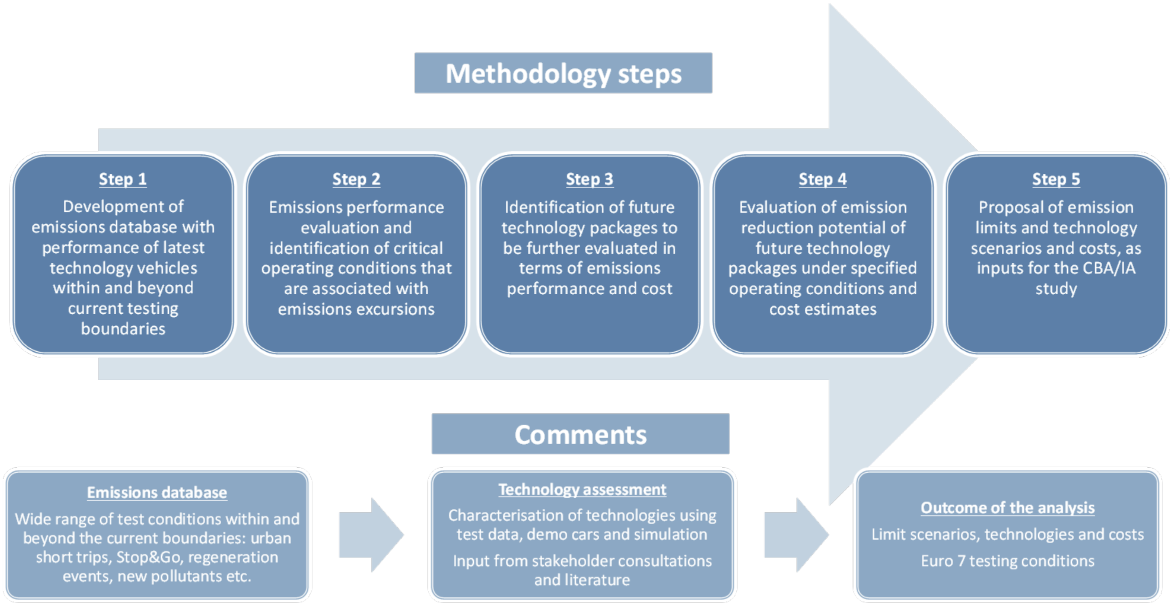

Figure 2-1: Methodology steps followed for the recommendation of emission limits and the determination of technology scenarios to be further evaluated in impact assessment study.

Step 1: Development of emissions database with test data from latest technology vehicles within and beyond current testing boundaries

A database has been set up to house all the emissions test data collected in the framework of the current study. The database is divided in two main parts, one for cars and vans, and the other part for lorries and buses. A detailed description of these databases is provided in Annex 2 of the present report.

For the part focusing on cars and vans, the database includes results from 72 vehicles, 19 of them complying with the Euro 6d standard and the rest with the Euro 6d-temp standard. The available data for vans were rather limited, thus only 4 vans (1 Euro 6d Class III, 1 Euro

6d Class II and 2 Euro 6d-temp Class II) are included in the database. This database includes measurement data from CLOVE partners (both from testing activity within the current framework contract and from own data) as well as from the JRC and other stakeholders. All fuel types are covered i.e., diesel, petrol, compressed natural gas (CNG), liquefied petroleum gas (LPG) and hybrid-electric vehicles. Petrol vehicles are classed in 10 categories based on their fuel injection system (e.g., petrol direct injection - GDI, port fuel injection – PFI, etc.) and hybridisation level (e.g., mild hybrids, plug-in hybrid electric vehicles - PHEVs etc.). Diesel vehicles are categorised as conventional, mild hybrids and PHEVs. As regards the emission control system, a wide range of different components and configurations are included, covering almost all the main configurations observed in the latest technology vehicles. As regards the test types, a wide variety of on-road (e.g., RDE-compliant tests, dynamic driving, short trips etc.) and chassis dynamometer tests (e.g., WLTC, TfL, RDE replication etc.) are included. Emissions data for these vehicles and tests include the currently regulated emissions species (i.e., CO, CO_2, NOx and SPN_{23} for RDE tests) and in the case of chassis dynamometer tests also the currently non-regulated emissions species (e.g., CH_4, N_2O, NH_3). Annex 2 of this report provides an overview and all the details about all these parameters (i.e., vehicles, test conditions and species measured).

As regards the lorries/buses database, it contains 10 Euro VI C and D vehicles, which were tested by CLOVE partners (both from the testing activity within the current framework contract and from own data). Different fuel and powertrain types were investigated (diesel, CNG, liquefied natural gas (LNG) and diesel hybrid). Tests were performed both on chassis dynamometer and on-road, covering all regulated emissions species as well as a wide range of currently non-regulated emissions species (both in the laboratory and a few on-road tests).

Step 2: Emissions performance evaluation using the CLOVE database and identification of critical operating conditions that are associated with emissions excursions (analysed in Chapters 4 & 5)

Following the development of the database, a critical analysis of the emissions data was performed. The target of this task was to evaluate the emission performance of latest technology vehicles. Particular attention was paid to the following driving situations and events that are associated with emissions excursions:

- Cold start - short trips (covering “stop-and-go” conditions)
- Low ambient temperature
- High engine power events/periods:
  - Harsh accelerations
  - Uphill driving, high vehicle payload and/or trailer pulling
  - High vehicle speed
- Idling and low load driving which may occur during traffic congestion (severe stop-and-go situations)
- Diesel particulate filter (DPF) regeneration and when the filter is clean
- High SPN emissions from technologies currently not covered by the regulation (PFI and gas engines)

The critical analysis of the emissions database and the identification of the critical operating conditions is conducted in Chapter 4 for cars/vans (LDVs) and Chapter 5 for lorries/buses (HDVs).

Step 3: Identification of future technology packages to be further evaluated in terms of emissions performance and cost (analysed in Chapters 7 & 8)

In contrast to the first and second steps which collated and reviewed performance of existing vehicles, the third step is a more forward-looking activity that aims to identify the potential future technologies that are going to be further evaluated (in Step 4). Step 3 integrates the following elements:

- Internal data, information and experience by the CLOVE partners concerning the development of emission control technologies
- Additional input coming from stakeholders (mainly the industry, including vehicle OEMs, suppliers and associations), either through direct consultation or by reviewing published work.

Taking into consideration the above, comprehensive emission control packages were developed with a number of potential future technologies separately for petrol (potentially applicable also to CNG and LPG vehicles) and for diesel cars and vans. These technologies are further evaluated in Step 4, in terms of emissions performance and cost.

Input to the development of these tables and the evaluation of the technology packages has come from stakeholders, either through direct consultation or by reviewing published work. In the context of this study, a number of stakeholder consultation activities have taken place, as summarised in the respective synopsis report including public and targeted consultations, bilateral discussions with industry stakeholders, as well as exchange within the Advisory Group on Vehicle Emission Standards (AGVES) through several workshops. Particular input on technologies and achievable emission levels has been received through the 2nd targeted stakeholder consultation, the relevant questions of which are presented in Annex 3 of this report. Through this direct communication with stakeholders, the emissions database has been further enriched with test data from demonstrator vehicles/engines that integrate potential future technology packages.

Additional emission control technologies and technology packages have been sourced in the literature and reviewed. Such information has been retrieved from published scientific papers, presentations in conferences, workshops, webinars and deliverables of research projects.

The relevant analysis and detailed presentation of the above elements is given in Chapter 7 for cars/vans (LDVs) and Chapter 8 for lorries/ buses (HDVs).

Step 4: Evaluation of emission reduction potential of future technology packages (selected in Step 3), under specified operating conditions and cost estimates (analysed in Chapters 7 & 8)

After the definition of the future technology packages in Step 3, their emission reduction potential was evaluated using the following tools:

- Simulations of the emission performance of technology packages, using tools and software available within the CLOVE partners.
- Test data from demonstrator vehicles integrating future technology packages, provided by stakeholders. Such data have been provided by the AECC and several engineering service providers, and submissions include light-duty diesel and petrol passenger cars, heavy-duty diesel and natural gas technologies.
- Emissions data collected during the consultations and retrieved from literature, including prototypes developed in the context of European research projects.

A particular focus has been on technologies intended to address high emissions in non-favourable driving conditions, such as those outlined in Step 2. The conclusions of the achievable emission reduction potential of future technology packages are conducted in Chapter 7 for cars/vans (LDVs) and Chapter 8 for lorries/buses (HDVs). The outcome of this step will be the main input for the final Step 5.

Step 5: Recommendation of emission limits, technology scenarios and costs to be included in the cost-benefit analysis of the impact assessment study (analysed in Chapters 7 & 8)

The final step of the approach is the recommendation of the possible EURO 7 emission limits, together with the corresponding technology scenarios and their costs. This set of recommendations forms an input for the cost/benefit analysis of the impact assessment study. The recommendations have been largely based on the outcomes of Step 4, concerning emissions performance, and on additional information and data on related impacts, either internal data from CLOVE or from stakeholders through the consultation activities and bilateral discussions (or the literature).

The recommendations of the technology scenarios with all the relevant details and costs are given in Chapter 7 for cars/vans (LDVs) and Chapter 8 for lorries/buses (HDVs).

3 Pollutants considered for inclusion in EURO 7

3.1 Summary of regulated and unregulated pollutants

This Chapter consists of several parts including the justification for including emission species in EURO 7 and issues related to measurement technologies, such as minimum recommended emission limits based on PEMS analyser capabilities. The topics covered in this chapter are as follows:

- *Recommended emission species to be covered in EURO 7*. Emission species recommended to be covered in the EURO 7 legislation were evaluated by considering their health and environmental impacts and potential presence in vehicle exhaust when using different engines, exhaust emission control and fuels. A wide array of emission species was evaluated based on air quality regulations, health risk classifications and literature (Table 3-1). In parallel, emission standards outside of the EU were taken into account (Table 3-2). As an outcome, the emission species recommended to be covered in EURO 7 are NOx, CO, SPN (nominally >10nm), PM, NH_3, N_2O, CH_4, HCHO, NMOG[1] and brake wear (PM & Total PN) emissions. Table 3-4 summarises these emission species together with justification for their inclusion in EURO 7. Brake wear emissions are discussed in Chapter 10.

- *Appropriate measurement technologies for selected emission species were evaluated.* Each of the emission species recommended for inclusion in EURO 7 were considered in the context of available measurement technologies to detect these emissions in vehicle exhaust, particularly as concerns possibilities for on-road measurements. The measurement technologies available are included in Table 3-3.

- *Recommendations whether to measure and limit emissions in laboratory or on-road.* Recommendations to measure and set emission limits for the emission species were evaluated based on the capabilities of measurement technologies to be used in on-road testing. Most emission species are recommended to be measured and limited on-road, excepting PM and NMOG (THC is needed for calculating NMOG), which are recommended to be primarily measured in-laboratory until suitable portable emissions measurement system (PEMS) technologies have been developed for on-road testing. Also, brake emissions are recommended to be measured in the lab due to the difficulty in defining the contribution of various non-exhaust sources accurately on-road.

- *Recommended minimum limits based on analyser capabilities.* Recommended minimum emission limit for cars, LCVs and HDVs were evaluated based on PEMS analyser capabilities, which are currently quite modest in analysing low concentrations, compared to the best laboratory analyser systems. This is understandable when considering the typical calibration gas concentrations, which may be e.g. CO 10 000 ppm, NO 1250 ppm and NO_2 625 ppm. High concentrations of calibration gases are needed to accurately measure instantaneous high concentrations; however, this diminishes accuracy at the low end of the measurement scale. Laboratory analysers may have two (or more) calibration gases. So, for PEMS, analyser dependent variability increments are recommended to be high (e.g. 3-4 times the Limit of Quantification (LoQ), 10 times the Limit of Detection (LoD)). One appropriate guideline for relationship between LoD and emission limit values is presented for raw gas (stack) emissions measurements by

[1] Non-methane organic gases

the UK Environment Agency (2021). Analyser capabilities are determined under ideal conditions, and many additional parameters should be considered for on-vehicle measurements with a portable system. These are included in the measurement uncertainty analysis and the regulation margin.

- *Initial recommendations to improve accuracy of measurements.* Technology improvements to the PEMS equipment are anticipated (e.g., lower LoD, low zero drift, calibration issues, improved Exhaust Flow Meter (EFM)). Additionally, calculation methods to treat concentrations close to the detection limit of the analyser would improve reliability of the results from low-emitting cars and vehicles. These issues and some quality assurance related requirements, such as validation of PEMS systems, are initially recommended to be considered in the implementation regulation. These development steps will enable lower limit values, as long as the capability for the equipment to also accurately and repeatably measure at engine development target levels is also ensured.

3.1.1 Harmfulness of emission species

Health and environmental impacts

Air pollution adversely affects the whole of an ecosystem due to many different direct and indirect pathways including harmful effects of toxic species, particles, acidifying compounds and others. For impacts of air pollutants, the EU policy framework has three cornerstones addressing the topic top-down: Green Deal/Clean air for all (COM(2018) 330), Air Quality (AQ) Directives, and the National Emissions Ceiling Directive (NECD). The significance of air pollution is stated for example in the Clean air for all Communication: *"…in many parts of the world, with 9 out of 10 people breathing air containing high levels of pollutants. Air pollution continues to be the number one environmental cause of early death in the EU, with estimates of more than 400,000 premature deaths per year."*

To limit environmental damage of air pollutants, the principal AQ regulation given in Directives 2008/50/EC and 2004/107/EC provide air quality objectives and limit values of air pollutants in ambient air, while the NECD (Directive 2016/2284/EU) sets 2020 and 2030 national emission reduction commitments for NOx, non-methane volatile organic compounds (NMVOC[2]), SO_2, NH_3 and $PM_{2.5}$. The NECD reporting requires information also on emissions of CO, PM_{10} (black carbon (BC) if available), total suspended particulate matter and the heavy metals Cd, Pb, Hg (and if available, As, Cr, Co, Ni, Se and Zn) and persistent organic pollutants (POPs), including selected polycyclic aromatic hydrocarbons (PAHs), dioxins and furans, polychlorinated biphenyls (PCBs) and hexachlorobenzene (HCB). International organisations are also evaluating health risk factors for calculating e.g., the cancer potency of substances. The EU has also introduced legislation addressing pollution at source, of which the Euro standards are one example. The Euro emission standards so far have reduced some air pollutants since the 1990s, particularly CO, NMVOC and NOx, while trends in $PM_{2.5}$ (after accounting for non-exhaust emissions) and NO_2 emissions from road transport has been less positive (EEA, 2017). NOx emissions from the road transport sector reduced by 63% between 1990 and 2018. However, transport sector is a major source of the ground-level ozone precursors contributing by 39% to NOx, 20% to CO and 8% to NMVOCs in 2018, in the EU. Transport sector is also a major source of primary $PM_{2.5}$, PM_{10}, BC and Pb emissions (EEA, 2019).

Engine exhaust is a mixture of many different constituents, and studies do not always decouple the effects of different exhaust species from each other, for example exhaust

[2] VOCs include in the EU e.g. hydrocarbons, alcohols, ethers, esters, and aldehydes having an initial boiling point <250°C at 101.3 kPa (Directive 2004/42/CE).

gases from exhaust particles, or solid nanoparticles from volatile and semi-volatile ones. Additionally, animal health impact studies may not accurately replicate human health responses, or what happens when exhaust gaseous species or particles enter the human body. Specific effects of some exhaust emission species, e.g., nanoparticles (transition metals, nanocarbon, nucleation mode), from vehicle sources have not been widely studied from modern emissions control technologies. Overall, adverse health impacts of exhaust are not always traceable to individual exhaust species. Notably, diesel engine exhaust is classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1), and petrol exhaust as possibly carcinogenic (Group 2B) (IARC, 2013). The U.S. EPA has also defined key mobile-source air toxics including 1,3-butadiene, formaldehyde, acetaldehyde, acrolein, polycyclic organic matter, naphthalene, diesel exhaust and petrol PM (2007 rule).

NO_2 is an air pollutant causing many harmful effects, such as irritation of the lungs and adverse respiratory effects. NO_2 may react in the atmosphere to form toxic products, contribute to the formation of ground-level ozone, acidification and, via nitric acid (HNO_3), eutrophication and changes in ecosystems. NOx, consisting of mainly NO and to a lesser extent NO_2, is produced in the combustion chamber from nitrogen in air. High concentrations of NO_2 can be formed in lean exhaust over precious metal-based catalysts (e.g., diesel oxidation catalysts - DOCs), while a TWC generally does not form NO_2 due to low levels of oxygen in the exhaust in stoichiometric combustion (Vallero, 2014).

NH_3 is a toxic and corrosive gas, and it is a precursor of secondary aerosols and smog causing adverse health, climate, and visibility impairment effects. NH_3 dissolved in rainwater falling on land and water bodies leads to eutrophication. NH_3 is a potential emission from the urea-based SCR systems for NOx control from diesel engines when unreacted ammonia slips to exit the tailpipe, and from TWC equipped stoichiometric engines during operation in slightly rich conditions (Mejía-centeno and Fuentes, 2005). NH_3 may also be formed by lean-NOx traps (LNT) in periodic excess fuel combustion events. NH_3 emissions of 20 mg/km from cars in the EU have been detected (Suarez-Bertoa et al., 2014).

N_2O is a strong greenhouse gas with a GWP of 265 on a 100-year basis (264 on 20-year basis) relative to CO_2. The lifetime of N_2O is 121 years (Myhre et al., 2013; Pachauri and Meyer, 2014). N_2O is a non-flammable, colourless gas commonly called "laughing gas" and is used e.g., as an anaesthetic agent, and it is not considered as a direct air pollutant, although e.g., breathing difficulty is associated with high N_2O inhalation. N_2O may deplete the stratospheric ozone layer when concentrations of halocarbons reduce (Seinfeld and Pandis, 2006; Portmann et al., 2012; Müller, 2021) and hence N_2O is regarded as an indirect air pollutant, since depletion of the stratospheric ozone layer increases cancer-causing UVB radiation at the surface of the Earth. N_2O may be induced by some exhaust emission control devices, e.g., DOC, LNT, DPF, SCR. For example, unreacted NH_3 can be transformed to N_2O across a mild oxidising catalyst (Guan et al., 2014; Nevalainen et al., 2018).

CH_4 has a high GHG impact having GWP of approx. 28 times higher on a 100-year basis than that of CO_2 (84 times on 20-year basis). Methane is not considered as a direct air pollutant, and it is also non-reactive having low ability to contribute to ozone formation (the Maximum Incremental Reactivity (MIR) value is only 0.012, compared to, for example, 9.00 for ethene) (Carter, 2010). In regions where background CH_4 is dominating and concentrations of other VOCs are very low, CH_4 contributes significantly to the formation of tropospheric ozone (Fiore et al., 2002; Isaksen et al., 2014; Dingenen et al., 2017). In polluted urban areas, the role of inactive CH_4 is low compared to the other VOCs in this respect. CH_4 emission is of concern especially when using methane as a fuel (natural gas, biomethane, synthetic methane) due to direct methane slip from engines, but it can also be formed via partial oxidation of other fuels.

Formaldehyde (HCHO) is classified as a human carcinogen (Group 1 IARC, 2012), and acetaldehyde as a possible human carcinogen. Both aldehydes cause irritation to the eyes, skin and respiratory tract and induce cellular inflammation. These aldehydes are reactive and contribute to the atmospheric photochemical system. Acetaldehyde is currently regarded as harmful at higher concentrations than formaldehyde. While HCHO is present predominantly indoors and acetaldehyde in e.g., some foods sources, transport contributes to ambient concentrations of aldehydes directly and through photochemical reactions. HCHO is potentially released from e.g., methanol- and methane-fuelled vehicles, but also from diesel engines (engine-out), while ethanol-fuelled cars tend to emit acetaldehyde and butanol fuelled cars C4-carbonyls, respectively.

1,3-Butadiene is carcinogenic to humans (Group 1) and it is reactive forming e.g., formaldehyde, acetaldehyde, and acrolein, which is irritant to the respiratory tract and chronic inhalation results in inflammation (HEI Air Toxics Review Panel, 2007). 1,3-butadiene is found e.g., in tobacco smoke. 1,3-Butadiene and acrolein concentrations are found to be low in vehicle exhaust gases.

The NMOG group includes organic compounds having different effects on human health and environment. Particularly of concern is the formation of the *ground-level ozone*, which causes adverse health effects, damages plants and increases global warming (Vallero, 2014). Ozone is not emitted directly from the tailpipe, it is a secondary emission formed by the precursor emissions of CO, reactive NMOG compounds and NOx in the presence of heat and sunlight via photochemical reactions. The ozone-forming potential (OFP) of individual compounds varies and can be calculated by using MIR factors (Carter, 1994). Some of the compounds in the NMOG group are more reactive and harmful than the others, while some of them, e.g., ethanol, are not regarded as harmful at ambient concentrations. Individual NMOG compounds emitted depend on the combustion source and fuel used, e.g., ethanol fuelled cars emit mainly ethanol, while aromatics or olefins may dominate NMOG emissions of other fuels.

Isocyanic acid (HNCO) is toxic, and it may be present in the exhaust from TWC, LNT or SCR equipped engines. In SCR, optimally no HNCO should appear in complete decomposition (Lehtoranta et al., 2015). Low HNCO emissions have been reported for SCR equipped diesel engines, and for Euro 5-6 PI engines and diesels with NOx storage catalysts at level of 1.4 mg/km at 23 °C. (R. Suarez-Bertoa and Astorga, 2016).

Many PAHs are carcinogenic and mutagenic, e.g., benzo(a)pyrene (BaP). Priority PAHs have been defined (e.g., 7 PAHs in 2004/107/EC) and the toxic equivalency factors (TEF) of PAHs relative to BaP is subject to an AQ limit (European Commission, 2001). Tobacco smoke and food-derived sources contain PAHs (HEI, 2007), but they originate also from unburned fuels, lubricants or they are formed in the combustion process. PAHs can be present in the PM and semi-volatile fraction of vehicle exhaust depending on gas-particle partitioning in sampling conditions (Aakko-Saksa et al., 2014b).

PM emissions are a major contributor to health threats of air pollution. PM adversely affects breathing and the respiratory system, damages lung tissue and causes premature deaths. Effects of particles on human health depend on their size and composition. PM constituents, such as black carbon (BC), organic compounds, metals, sulphates, and nitrates are formed in the combustion of fuel and lube oil, and in emission control devices. PAHs are present in PM as mentioned. One PM constituent, BC, is the second strongest contributor to climate change after CO_2, while some other constituents have a cooling effect on climate (Bond et al., 2013). From cars, very low PM and PN emissions indicate low BC emissions, and BC is indirectly included in PM and non-volatile PN limits. For Euro 6a petrol cars the share of BC in PM emission is 50% or higher, while for E85 flexible fuel vehicles it is very low (Aakko-Saksa P. et al., 2019). Primary PM and semi-volatile compounds contribute to the formation of secondary aerosols in atmospheric reactions with natural and anthropogenic VOCs. Secondary aerosols are also associated with adverse health effects and deserve consideration besides tailpipe emissions when the transport sector’s emissions are assessed (Gramsch et al., 2018; Timonen et al., 2017).

Small particles penetrate deeply into the lungs and can cause or worsen respiratory disease and aggravate existing heart disease, while coarse particles are removed e.g., by swallowing or coughing. More than 90% of diesel particles are ultrafine (<0.1 μm) and can reach the alveolar region of the lung and potentially pass into the blood stream then concentrating in critical organs and leading to acute and chronic health effects. Nanoparticles <50 nm may be present at high concentrations in vehicle exhaust. Diesel particles have a large surface area potentially adsorbing toxic, mutagenic, and carcinogenic compounds, e.g., PAHs. (HEI, 2002; Kittelson, 2002; IARC vol 109, 2016). Particle uptake by cells is greater for <50 nm than for larger particles, and nanoparticles enter cells in several areas in the body (Hankin, 2008). High specific particle surface area leads to greater inflammation reflecting greater uptake, or carriage of inflammatory chemistries.

Particle number emissions currently regulated refer to non-volatile, solid SPN >23nm. Since Euro 5b, particle filters have effectively controlled SPN (>23nm) from diesel cars, and more recently from petrol direct injection engines. Filtration efficiencies are generally highest with DPF, reducing PN emissions from ~$5x10^{13}$#/km (engine-out) to as low as $5x10^{8}$#/km (tailpipe). Petrol PN concentrations are lower in-cylinder, but GPF efficiencies (although lower than the DPF ones) lead to tailpipe levels of ~10^{11}#/km or lower. During active regenerations, tailpipe PN concentrations post-DPF elevate for short periods, but are still below engine-out levels. Recently, SPN below 23 nm was reportedly present in exhaust from both CI and PI engines (Giechaskiel et al., 2018b). Two and more additional orders of magnitude of SPN <23nm was found in the exhaust for e.g., petrol PFI and CNG light duty vehicles for which there is no requirement to control PN emissions. HD gas applications are subject to the same PM and PN requirements as HD diesels, while port-fuel injected petrol engines and gaseous fuelled applications are not currently subject to PN or PM legislation. These applications may have in-cylinder soot concentrations lower than GDI (10^{4} – 10^{5}/cm^{3}), and very low PM emissions, although in the absence of soot in-cylinder solid nanoparticles may exist. In technologies with higher in-cylinder soot concentrations these solid nanoparticles are captured on the surface of soot agglomerates. Total PN (TPN) is the third property of particle number emissions, referring to sum of non-volatile and volatile particle number emissions. This can be at least as high as engine-out solid particle emissions from non-DPF diesels (~10^{14}#/km from light-duty diesels).

The significance of the new emission species depends on their harmfulness and contribution to the ambient air concentrations. Table 3-1 summarises the emission species, their mobile sources, limitations in current standards and harmfulness (Annex 2 explains in more detail the classification of mobile source air pollutants to different priorities).

Table 3-1: The assessment of emission species for recommendations

	Mobile sources and limits in current standards	Harmfulness (framework)
NO_2	Emission control devices. *Note:* ***Limited*** *within NOx.*	Health, environment, ozone formation (AQ pollutant).
NH_3	Emission control devices. *Note:* ***Concentration limit*** *for Euro VI engines*	Health, environment. Secondary aerosols with PM. (AQ pollutant).
N_2O	Emission control devices	Strong GHG. Global warming (IPCC). Stratospheric ozone depletion.
NMOG	E.g., alcohol fuels. *Note:* ***Partly limited*** *within THC.*	Health. Ozone formation.

	Mobile sources and limits in current standards	Harmfulness (framework)
Methane	Fuel related. *Note:* ***Partly limited*** *(HD engines and within THC).*	Strong GHG. Global warming (IPCC). Tropospheric ozone formation.
Formaldehyde (HCHO)	Combustion (e.g., methanol fuel, diesel engines)	Health, environment (ozone), US EPA.
Particles **e.g., SPN_{10}**	Fuel, lube, combustion, brakes, tyres. *Note:* ***Limited partly*** *as SPN_{23}*	Health. Global warming through BC.
Acetaldehyde	Combustion (ethanol fuels), fuel oxygen	Health, environment (ozone), less harmful than formaldehyde.
Ethanol	Fuel related (ethanol fuels)	Harmful at high concentrations.
Isocyanic acid, cyanides	Emission control devices. Low concentrations.	Health.
Ozone (tropospheric)	Ozone is a secondary pollutant induced by VOC and NOx (not emitted from the tailpipe)	Health, environment.
1,3-Butadiene	Combustion of fuel, potentially some emission control devices. Low concentrations. Possible to limit through fuel olefin content.	Health, environment.
Acrolein	Secondary emission mainly, formed by 1,3-butadiene emission	Health, environment.
Toluene, xylenes	Fuel related mainly. Could be limited through fuel quality.	Health.
Secondary aerosols (SOA/SIA)	PM, NH_3, SVOC, aromatics, PAH etc. are secondary emissions (not from tailpipe). Precursors could be limited.	Health, environment.
Dioxins and furans	Fuel and oil additives. Could be limited through fuel and oil chlorine content.	Health.
Benzene, PAH, metals	Fuel and oil related, engine wear metals. *Note:* ***Partly limited*** *by fuel quality standard*	Health. PM and semivolatiles may carry these species.
Pb, SO_2[3]	Fuel related. *Note:* ***Limited*** *by fuel quality standard*	Health, Environment.

[3] Sulphur content of on-road fuels is regulated to <10 mg/kg, which has led to very low SO_2 emissions from transport in the EU. SO_2 is a respiratory irritant, damages crops, and causes visibility problems. Sulphur oxides form acids in the atmosphere (acid rain) causing damage to crops and materials (Vallero, 2014).

3.2 Emission standards outside of the EU

Emissions species which are currently not regulated as mass emissions in the EU but are regulated in regions outside of the EU include NMOG, HCHO, CH_4, N_2O, NH_3 and NO_2 emissions as presented in Table 3-2 (Further details are provided in Annex 1 of the Annex Report). Not all of these emission species are directly limited in any of the regions, and different calculation and testing procedures apply. There are also emissions species not currently regulated worldwide and that are the subject of scientific studies or research projects to be considered for coverage in the future. It is noted that PN<23nm non-volatile Particle Numbers are not directly regulated in any region worldwide.

Table 3-2: Additional emissions species (not currently regulated in EU)

	Other pollutants coverage
US	**LDV: NMOG**[a], **HCHO, CH_4, N_2O** **GHG: CO_2, N_2O, CH_4 Scheme 1**: Respect limit of N_2O (0.00621 g/km) and CH_4 (0.00186 g/km) for each type and not include in GHG calculations. **Scheme 2**: Include measured N_2O and CH_4 in fleet averaging GHG programme without a requirement to respect the limit. **HCHO** EPA Tier 3 limit of 0.0025 g/km in all available bins (not a fleet average limit). **HD-engines: HCHO, N_2O, CH_4, NO_2, NH_3** **HCHO:** EPA 2010 standard (latest) 0.022 g/kWh HCHO limit for diesel/petrol HD engines. **N_2O and CH_4** (started MY 2015, consistent with LDV). Engine testing (tractors & vocational, FTP): N_2O = 0.136; CH_4 = 0.136 g/kWh. Chassis testing (pick-ups and vans, 55% FTP-75 + 45% HWFET): N_2O = 0.03 g/km; CH_4 = 0.03 g/km (averaging between vehicles not allowed) **NO_2** limit for retrofit catalysts. Limits the increase in NO_2 emissions associated with some retrofit technologies to 20% of the engine NO_2 levels without the retrofit. **NH_3** <=25 ppm on average over any test cycle used to support emission reduction claims.
China	**LDV: N_2O, CH_4** **N_2O** (China 6a+6b) Category 1: 0.02 g/km. Category 2: cl1: 0.02 g/km, cl2: 0.025 g/km, cl3: 0.03 g/km China 6 regulation limits indirectly **CH_4** (through THC and NMHC). Future outlook: NH_3 limit, aldehydes **HD-engines:** China VI - NH_3 limit: 10 ppm
South Korea	**HCHO** for PI vehicles: For vehicles fuelled by alcohol only or alcohol bi-fuel: limit for HCHO (0.0025 g/km). **NH_3:** For petrol/LPG powered vehicles: Large-sized (3500kg ≤ GVW< 15000kg) and extra-large PCs NH_3 <= 10 ppm after January 2013. For diesel powered vehicles: Large-sized (3500kg ≤ GVW< 15000kg) and extra-large PCs: NH_3 <= 10 ppm
Brazil	**NH_3:** From the **PROCONVE L8** Phase, that will come into effect in 2025, NH_3 emissions of CI vehicles equipped with SCR systems will be limited to 10 ppm. **NMHC and aldehydes**[b]**:** Regulations cover NMHC (Otto and diesel) and aldehydes (Otto cycle).

[a]: combined NOx + NMOG limit. NMOG determined as in US 40 CFR § 1066.635 (paragraph a): adding oxygenated species to NMHC, which is calculated by subtracting CH_4 and oxygenated species with FID response factors from THC (FID) emissions (U.S. GPO, 2016b). Alternative methods include NMHC = NMOG for non-petrol vehicles, and for up to 25% vol. EtOH in petrol NMOG proportional to NMHC (FID-based). For >25% EtOH, US 40 CFR § 1066.635 (paragraph f): "…manufacturers may propose a methodology to calculate NMOG results from measured NMHC emissions. We will approve adjustments based on comparative testing that demonstrates how to properly represent NMOG based on measured NMHC emissions"
[b]: OEMs have an option to subtract the ethanol emission (impinger/GC measurement) from the NMHC result (THC(FID) minus CH_4). In this case, the NMHC result includes partial contributions from aldehydes, but does not address ethanol emissions completely (Dallmann and Façanha, 2017).

The definition of NMOG emissions when using alcohol fuels is not straightforward. NMOG is included in the regulations in the US as a combined NOx + NMOG limit. In the US, many calculation procedures of NMOG emissions are defined depending on the engine and fuel.

The need for an accurate measurement of the concentration of oxygenated species in vehicle exhaust is case-specific (Table 3-2, footnotes).

In Brazil, the LDV fleet is dominated by flexible fuel vehicles capable of using a blend of petrol and anhydrous ethanol (gasohol) or ethanol. The regulations in Brazil cover NMHC (petrol and diesel) and aldehydes (petrol). However, OEMs have an option to subtract the ethanol emission (impinger/GC measurement) from the NMHC result (FID-based). In this case, the NMHC result does not address ethanol emissions (Dallmann and Façanha, 2017).

3.3 Measurement technologies

CO, THC and NOx emissions are traditionally analysed in laboratory from the Constant Volume Sampler (CVS) diluted exhaust gas samples (Tedlar bags). NOx emissions are analysed by Chemiluminescence Detection (CLD) in the laboratory. This adds complexity through the use of an ozone generator but has been successfully used in some PEMS. The Non-Dispersive Ultra Violet Spectroscopy (NDUV) technique is common for measuring on-vehicle NOx and NO_2, and the Non-Dispersive Infra-Red (NDIR) technique for measuring CO and CO_2 emissions. For NDUV, the NO and NO_2 signals occur in the wavelength of H_2O and so interferences will occur, and signal detection is challenging at low NOx concentrations (Cao et al., 2016). Flame ionisation detector (FID) analysers are available for THC measurements in laboratory and for on-road testing of HDVs but restricted for cars due to the need for combustible FID-fuel gas (H_2/He mix). For research purposes, a combination of different sampling and analysis techniques in laboratory measurements is used to characterise e.g., individual hydrocarbons, carbonyl compounds and PAHs.

For on-vehicle measurements of new species, quantum cascade lasers (QCL) is one of the promising techniques capable of measuring NO, NO_2, N_2O and NH_3. QCL uses the absorption spectra of exhaust gas in the mid infra-red region. The measurement range and resolution are good, and a fast response can be achieved. The QCL technique can also be applied to other components of exhaust gases, but in each case a dedicated laser source is required.

The Fourier transform infrared (FTIR) technique is capable of analysing a wide set of compounds in on-vehicle measurements, such as CO_2, CO, NO, NO_2, NH_3, N_2O, HNCO, CH_4, alcohols, aldehydes, and ethers. PEMS-FTIR instruments are already available on the market. Challenges in on-vehicle FTIR measurements include the cooling of the detector with liquid N_2 (other cooling media may be possible) and span/purging consume nitrogen. A longer optical path of the interferometer improves the resolution of FTIR (mirror movement, e.g., 2 cm defines 0.5 cm^{-1} resolution), however, at the cost of the number of scans performed. Calibrations of FTIR instruments are practically unnecessary, other than OEM calibrations. The correlation between FTIR and traditional analysers have been studied (Gierczak et al., 2017; Aakko-Saksa 1994, 2011, 2014). In the CLOVE HDV testing, several FTIR instruments used in on-vehicle measurements showed good performance in comparison with PEMS-UV, CLD and sensor for NOx, with GC for CH_4, and with 2,4-dinitrophenylhydrazine/high-performance liquid chromatography (DNPH/HPLC) for HCHO emission. Other methodologies and instruments than those presented here are entering the market for measuring new exhaust species and for on-vehicle measurements, and prototypes have been introduced e.g., by VirtualVehicle[4].

Smart Emission Measurement System (SEMS) is a sensor-based measurement system including an on-board power source, having limitations on accuracy e.g., 10% variations with current PEMS and laboratory results. This system can be used for on-vehicle

[4] www.v2c2.at

measurements to gain real-time data with minimum or no calibration requirements. An example of such a system is a prototype SEMS for NOx and NH_3 emissions from TNO (Van der Mark, 2016). Also, the company ECM has its own sensor-based system with NOx, NH_3 and Lambda sensors[5]. Recently, integrated NOx and lambda sensors in miniature Pegasor Particle Sensors (PPS) was introduced.

In the laboratory, PM measurements are quantified gravimetrically. PM is diluted in either full flow dilution systems (FFDS) or partial flow dilution systems (PFDS), where the exhaust dilution regime is selected to avoid water condensation on the filter. Both systems sample a fixed proportion of the exhaust emitted by the vehicle, though in the case of the FFDS this is 100%. The consistency of sampling volatile materials is enhanced by maintaining the filter face temperature in the range of 42 to 52°C and using a narrow band of filter face velocities around 100 cm/s. Filter media are prescribed as either Teflon coated glass-fibre, or Teflon membranes. The latter require rigorous dispersion of static charges prior to weighing. Acquired mass on the filter is determined by differential weighing using a microbalance of 0.1µg resolution in a clean-room environment: room or weighing chamber. As the sample on the filter represents the emission of a fixed fraction of the total exhaust flow during the test, it is a straightforward task to correct the fraction to total mass emitted and then convert this to per km emissions for light-duty vehicles and per kWh emissions for heavy-duty engines. PM is not currently measured by PEMS for cars, nor recommended for measurement on-board any vehicles in Europe, although prototypes were tested, and it is included in some PEMS systems designed for HDVs. Real-time PM emission is measured from vehicles and engines based on e.g., photoacoustic spectroscopy measurements (e.g., Micro Soot Sensor in PEMS, measuring BC).

Particle number (PN) measurements in the laboratory are carried out by equipment developed according to the technical prescriptions defined in the Particle measurement programme (PMP). As with PM, these systems sample from exhaust diluted in FFDS or PFDS (the latter for HD only). The sample drawn from the dilution system passes through a pre-classifier, which sets a nominal upper particle size limit of 2.5µm and then into a volatile particle remover (VPR). The VPR uses hot dilution and an evaporation tube to force volatiles and semi-volatiles into the gas phase, and subsequent cold dilution to freeze particle evolution and prevent recondensation of evaporated volatiles. The non-volatile particle concentration in diluted exhaust (volatility defined by the conditioning process) is then enumerated using a condensation particle counter (CPC) with a defined counting efficiency of ~50% at 23nm. The concentration of particles in the diluted exhaust, plus the total exhaust flow from the vehicle or engine (following correction for dilution and the fraction of exhaust sampled), are used to determine the total particles per test, and from there particles per km and per kWh figures are simply generated for >23nm particles (PN_{23}). Calibration procedures include correcting for particle losses, volatile particle removal efficiency and counting efficiency of the CPC.

Recent developments within PMP supported by the results of the Horizon 2020 projects DownToTen, PEMS4Nano and SUREAL-23 have led to a new recommended regulatory text that reduces the lower size limit of PN methodology from 23nm to ~10nm (PN_{10}). The main changes include maximising transmission of particles >10nm through the VPR, recommending the use of catalytic evaporation tubes, changing the 50% counting efficiency to ~7nm (~70% at 10nm) and modifying calibration procedures.

PEMS equipment includes similar components and use the same principles as lab-based systems. Both Diffusion Charge (DCs) and CPCs are allowed, and the complete system needs to fulfil some efficiency requirements that match the PMP systems. As with PN_{23}, PEMS systems measuring PN_{10} are highly similar in principles and function to those to be used in the laboratory. Both CPC and DC particle counters are anticipated for use. Finally,

[5] A summary of these low-cost measurement systems can be found in a relevant presentation in a PEMS Workshop in 2018 (Johnson, 2018).

there is a cost associated with the change from PN_{23} to PN_{10}. While some PN_{23} systems (both lab and PEMS) may be upgradable to PN_{10}, this is not the case with all. Investment will be required to upgrade (limited) or replace (substantial) PN_{23} systems with PN_{10} (Samaras et al. 2021).

A summary of measurement techniques used in laboratory and their suitability in on-vehicle measurements for new emission species is shown in Table 3-3 below.

Table 3-3: Summary of measurement techniques for unregulated pollutants

	Laboratory	On-vehicle potential	Interference	Exhaust sample
NO_2	Dual - CLD[a]	Yes	CO_2, H_2O, NH_3, carbonyls	Diluted & raw exhaust. NO_2 calc NOx-NO – heated &wet
	NDUV[a]	Yes	H_2O, SO_2	Diluted & raw exhaust
	QCL[a]	Promising	H_2O, CO, CO_2	Diluted & raw exhaust
	NDIR[a]	Moderate	Pressure, H_2O	Diluted, dry
	FTIR	Yes	H_2O, CO_2	Raw exhaust
NH_3	LDS[a]	Yes		Raw exhaust
	QCL[a]	Promising	See above	Diluted & raw exhaust
	FTIR[a]	Yes	See above	Raw & dilute exhaust
N_2O	CG-ECD[a] (electron-capture detector)	No		Diluted exhaust (CVS bags)
	QCL[a] (laser IR)	Promising	See above	Diluted or raw
	NDIR[a]	Yes	See above	Diluted, dry
	FTIR	Yes	See above	Raw & dilute exhaust
Methane	GC-FID[a] (flame ionisation detector)	No (gas bottles)		Diluted
	NMC-FID[a] (non-methane cutter)	Low (gas bottles)		Diluted
	QCL[a] (laser IR)	Promising	See above	Diluted or raw
	FTIR	Yes		Raw exhaust

	Laboratory	On-vehicle potential	Interference	Exhaust sample
Formaldehyde (HCHO), acetaldehyde	DNPH & HPLC (UV/DAD)[b]	Low		Diluted
	PTR-MS (Proton Transfer Reaction)	Low		Diluted
	QCL[a] (laser IR)	Promising	See above	Diluted or raw
	FTIR[a]	Yes		Raw or dilute exhaust
Ethanol	Impinger & GC[a] PAS[a] PTR-MS[a] FTIR[a]	Low Yes		Raw for FTIR, but diluted for others
PN <23nm	PMP based approach (GTR 15); H2020 Projects Outputs	Same as lab using dedicated PEMS variance	Artefacts under investigation	Diluted (CVS); Raw facility and on road raw PEMS
TPN	Not included	Yes	Artefacts and sampling approaches to be explored	Diluted (CVS); Raw facility and on road raw PEMS
Brake wear [c]	Potentially included-gravimetric and particle counting methods	Possible	Artefacts and sampling approaches to be explored	Diluted and undiluted sampling

[a]: In the GTR-15 A5 proposal or known to be under development
[b]: Ultraviolet (UV) or diode array detector (DAD)
[c]: Measurement approaches defined by PMP

3.4 Recommended emission species for EURO 7 and their measurement

In diesel combustion, engine-out THC and CO are typically at low levels, while elevated NOx and PM emissions need to be controlled by e.g., SCR and DPF. Cars operating close to stoichiometric air to fuel ratio (e.g. petrol cars) can use TWC exhaust emission control, which efficiently reduces CO, THC, and NOx emissions. However, harmful species are also formed over the catalyst. Some emission species of concern are related to the introduction of new fuels (e.g., methane and alcohol fuels) or fuel additives, lube oil or engine-wear.

In the EU, CO, THC, NOx, PM and non-volatile, "solid" particles >23nm (SPN_{23}) are currently regulated, and an NH_3 cycle-average limit of 10 ppm applies to Euro VI diesel and gas engines (but not to Euro 6 cars or LCVs). NMHC and CH_4 are regulated for heavy-duty engines. Some emissions are regulated indirectly through fuel quality (e.g., SO_2, Pb, benzene and fuel-originating polycyclic aromatic hydrocarbons, PAHs). Lubricant-originating PAHs or PAHs formed in combustion are not controlled. Some harmful species emitted by cars and vehicles are neither directly included in the vehicle emission standards in the EU, nor indirectly regulated.

The recommendations on the exhaust emission species from vehicles and cars to be included in EURO 7 were developed by considering:

a) The adverse impacts of different species and the actual emissions from current, and potentially near-future vehicle engineering relative to the concentrations at which adverse impacts occur. (Chapter 3.1).
b) Emission standards outside of the EU (Chapter 3.2).
c) The availability and practicality of measurement technologies to accurately detect and quantify the emission species (Chapter 3.3).

Based on the evaluation, the recommended new gaseous pollutants to be covered are NH_3, N_2O, CH_4, NMOG and formaldehyde (Table 3-4). NH_3 potentially induced by exhaust emission control devices (e.g., SCR and TWC) is recommended to be limited individually. CH_4 emission is related to the use of methane fuels, while N_2O is induced by emission control devices (e.g., DOC, LNT, DPF, SCR) reducing NOx emissions from diesel engines. CH_4 and N_2O are recommended to be controlled and their levels accurately determined, but two options are identified for limiting these emission species: a) limiting CH_4 and N_2O emissions separately, or b) limiting the sum of CH_4 and N_2O expressed as a total cap. Securing technology neutrality needs special consideration when setting limits for CH_4 and N_2O emissions, since one pollutant is related to gas and the other to diesel technology. HCHO is harmful at very low concentrations, and potentially emitted from alcohol and diesel engines, hence it is recommended to be limited individually. Extending THC to NMOG emissions considers aldehyde and alcohol emissions originating from oxygenated fuels. NO_2 is not recommended to be limited as an individual species; instead, the NOx limit is recommended to be sufficiently low such that the NO_2 is also sufficiently controlled.

Vehicular particle mass and number emissions are also recommended to be covered in EURO 7. Filter-based PM is to be retained, to ensure that volatile materials excluded by solid particle methods are quantified. Transferring this from the laboratory to on-vehicle is possible, but practicalities must be understood. The application of particle filters to diesel and petrol engines renders the measurement of tailpipe PM effectively irrelevant in Europe, as compliance with the PN standard of $6x10^{11}$#/km ensures compliance with the PM limit of 4.5mg/km, and the PN standard correlates with a (solid) PM emission of approximately <0.4mg/km using the European filter-based approach. However, PM also includes semi-volatiles to a certain extent, which are currently not part of the PN regulation.

In order to detect metal oxides and other <23nm particle emissions, the current regulatory SPN_{23} metric will be replaced by a similar method with a lower size threshold in the range of 7-10 nm (SPN_{10}). These independent modes of non-volatile nanoparticles below 23nm are potentially present at concentrations similar to those of non-DPF diesel (~10^8 #/cm^3) and so are clear drivers for the development of <23nm SPN legislation. Future legislative activities should recommend the fitment of efficient particle filters to all ICE in order to reduce non-volatile particles of all chemistries including BC.

Brake wear particles measured from a brake dynamometer are subject to development within the Particle Measurement Program (PMP); preliminary discussions on how a regulation might be constructed were held in January 2021. Brake wear particles are discussed in Chapter 11.

Table 3-4: List of emissions species recommended to be covered in EURO 7 regulation and available measurement technologies

Emission species	Environmental issue	PEMS available Traditional/New	Measurement technologies
Currently covered, recommended to be included in EURO 7			
Nitrogen Oxides, NOx (*)	AQ ([a, b, c, d, e, h])	Yes/Yes	Dual CLD, NDUV, QCL, FTIR / on-board PEMS could be by QCL or FTIR.
Carbon Monoxide, CO	AQ ([a])	Yes/Yes	NDIR, FTIR /PEMS NDIR currently poor. Improvement needed (e.g. PEMS FTIR or QCL).
Solid particles, SPN	AQ ([a])	- /Yes	SPN_{23} available. SPN_{10} at the market-ready stage. PMP work.
Particulate matter, PM	AQ ([a, g, h])	Yes (not for cars)	PM-PEMS used for HDVs is not practical for cars.
Currently not covered, recommended to be included in EURO 7			
Ammonia, NH_3	AQ ([a, c, d, h])	- /Yes	LDS, QCL, FTIR / on-board PEMS could be QCL or FTIR.
Nitrous Oxide, N_2O	GHG & AQ ([a, f])	Yes/Yes	GC-ECD, QCL, NDIR, FTIR / on-board could be FTIR or QLC.
Methane, CH_4	GHG & AQ ([a, d])	Yes (not for cars)/Yes	FID with cutter, GC-FID, FTIR / on-board could be FTIR.
Formaldehyde, HCHO	AQ ([a, b, d])	- /Yes	DNPH&HPLC, PTR-MS, FTIR / on-board could be FTIR.
Non-Methane Organic Gases, NMOG	AQ ([a, b, e, h])	- /Calculated	Four options listed below the table.
Brake wear (PM & Total PN)	AQ ([a, g, h])	-/-	PM measured gravimetrically – PN measured by particle counting technologies - PMP work ongoing (see Chapter 10)

[a]: health, [b]: vegetation, [c]: acidification, [d]: eutrophication, [e]: tropospheric ozone, [f]: stratospheric ozone, [g]: global warming by black carbon, [h]: secondary aerosols, * NO_2 is controlled within the NOx limit, if limit is sufficiently low.

NMOG emission is a specific case, since it is calculated from THC emissions, CH_4 and oxygenated hydrocarbons. The definition “NMOG” means organic gases other than CH_4, and this group can be measured with many methods and principles similar to the other emission species. Accurate determination of NMOG emission requires measurements of many relevant oxygenated hydrocarbons. Four different procedures are listed as options for determining NMOG emissions, and from listed options one or several should be selected in the implementation regulation:

- A) To follow the US approach, principles, and measurement methodology.
- B) Measurement of NMOG emissions to be calculated by adding alcohols (methanol, ethanol) and aldehydes (formaldehyde, acetaldehyde) to NMHC emissions. Other

oxygenated hydrocarbon emissions considered depend on fuel composition, e.g., butanol and butyraldehyde emissions when butanol-containing fuels are used. In this case, NMHC emissions are calculated by subtracting CH_4 and oxygenated hydrocarbons with their FID response factors from THC (FID) emissions.

- C) Simplified measurement of NMOG emission by using equation: THC(FID) minus CH_4 plus HCHO. Approximate NMOG emission can be calculated using this methodology, since FID has response factors for all hydrocarbons, also hydrocarbons in oxygenates (other than HCHO). An example is given assuming exhaust gas to be 100% ethanol: FID response factor for ethanol is 0.75, meaning that NMOG measured by FID is 0.75 x true NMOG concentration. Furthermore, higher density used for ethanol exhaust in the calculation leads to the final NMOG result close to the true NMOG emissions. Simplified procedure enables determination of NMOG emission with common instruments, although some oxygenated hydrocarbons may be underestimated depending on its response factor.
- D) NMOG calculation from THC emission measured by other principle than FID combined with measurements of CH_4 and oxygenated hydrocarbon emissions can be suggested. New methodologies need to be validated.

Table 3-5: Recommendations for measuring and limiting emissions on-road or in-laboratory

	NOx	CO	SPN_{10}	PM	NH_3	N_2O	CH_4	HCHO	NMOG	THC
Measured or not	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Calc. (2)	Yes
LIMIT on-road	Yes	Yes	Yes	No (3)	Yes	Yes (1)	Yes (1)	Yes	No (3)	No (3)
LIMIT in-lab	No (4)	No (4)	No (4)	Yes	No (4)	Yes (1)	Yes (1)	No (4)	Yes	No (4)

Testing procedures are described in Chapter 6.
(1) Option a. To limit N_2O and CH_4 individually. Option b. To limit sum of N_2O and CH_4 emissions.
(2) THC, HCHO, CH_4 need to be measured as a minimum for calculation of NMOG, but other emissions may be needed (see list of four options).
(3) If PEMS is sufficiently accurate and vehicle installation is practical, NMOG, THC and PM can be measured on-road subject to the same limits as in-lab.
(4) On-road limits apply, if measured in-laboratory on chassis or engine dynamometer.

PEMS systems for on-road measurements of low-emitting cars and vehicles are on the market for many emission species, but not for all of those recommended for inclusion in EURO 7. NOx, CO, SPN_{10}, NH_3, N_2O and HCHO can be measured and limited based on on-road testing (Table 3-5). PEMS systems are available for on-road measurement of PM and THC emissions from HDVs, but not from cars and consequently, these emissions are recommended to be measured and limited primarily based on in-laboratory testing. PEMS systems develop justifying allowance of measuring all emission species limited on-road when PEMS requirements are met, and on the other hand, simulation of on-road testing in-laboratory is justified for example when ambient temperature variation is narrow in the time of testing. Hence, emission limits set for in-laboratory testing are recommended to apply also for on-road testing, provided that PEMS systems meet the required specifications. Similarly, limits set for on-road measurements are recommended to be applied also to in-laboratory testing. This principle allows measurements of the relevant emissions species not only always in on-road conditions, but also in the laboratory with high accuracy. Testing procedures for cars, LCVs and HDVs are described in Chapter 6.

Some less harmful emission species are not recommended for inclusion in EURO 7, or they are included in the emission groups, e.g., ethanol and acetaldehyde emissions are regarded to be sufficiently limited in the group of NMOG, as they are detected by FID (response factor for e.g., ethanol is 0.75). Some emission species, although recognised as being detrimental to health, and are potentially formed by mobile sources, are challenging to measure at low concentrations, for example isocyanic acid (HNCO) and 1,3-butadiene. Challenges are faced also with the complexity of measuring low concentrations of ozone, acrolein (also a secondary pollutant from 1,3–butadiene), PAHs, semivolatiles, secondary aerosols, As, Cd, Ni and dioxins, particularly in on-board testing.

Some species are indirectly regulated, e.g., BC is regulated through particle related limits (PM and SPN). Similar arguments apply to many other toxic or environmentally damaging compounds that are emitted in low concentrations. PAHs are recognised as harmful species potentially present in the exhaust emissions. PAHs are included in the diesel fuel quality standard, but they may originate also in combustion, and are present in unburned mineral lubricant, but are trapped by a DPF and eliminated in regeneration. Benzene is included in the petrol fuel quality standard and an olefin limit of petrol was discussed in relation to 1,3-budiene emissions, although is not currently limited. Dioxin emissions are limited through the control of diesel and petrol fuel chlorine content to trace levels, while typical lubricant chlorine levels are voluntarily limited by producers, and consumption corresponds to sub-ppm fuel levels.

In the future, further changes in vehicle and exhaust emission control technologies or fuels and further developments in measurement techniques may lead to the need for further (re-) consideration of emission species. In some cases, more knowledge is needed to achieve reliable results, for example as concerns the following emission species even when the focus is on laboratory measurement developments:

1. PAHs in PM and semi-volatiles: More knowledge is needed to collect representative samples for PAH analysis combining PM and semi-volatile fractions of exhaust.
2. Secondary aerosols: Measurement technology needs development before achieving the level required for inclusion in emission standards.
3. Total particle number (TPN): To be considered for inclusion (also including the <23nm fraction) when input from e.g., PMP results are available for determination of sampling and dilution approaches. TPN regulation over a wide size range will present significant challenges, since the formation of volatile particles will be highly dependent on dilution, residence time and sampling conditions, so standardisation of these will be critical to the viability of regulating TPN. TPN is already considered for brake particle emissions at the PMP level.
4. Tyre Wear (PM and Total PN): The potential control of tyre wear particles may also be explored by the PMP group (see Chapter 10) as well as being the subject of a recent H2020 call. However, currently measurement capability is at the early stages of development.

Comprehensive “no harm” testing, such as biological or oxidative potential testing, could be used to screen harmfulness of total exhaust without chemically analysing the individual emission species. “No harm” testing of selected new technologies could be a cost-efficient way to identify potentially harmful exhaust.

3.5 Recommended minimum emission limits for EURO 7 based on PEMS analyser capabilities

The emission limit value (ELV) should be set at the emission level that can be reliably analysed. One appropriate guideline for raw gas (stack) emissions measurements states that *"The percentage uncertainty associated with a measurement increases the closer the result is to the LoD. Some manual methods specify a LoD as a fixed percentage of the ELV (usually 10%). This provides a guide for selecting an appropriate sample time and helps minimise the uncertainty associated with a measurement result that is close to the ELV."* (Environment Agency (UK), 2019). This parameter, called here **analyser dependent variability increment** (e.g., 3-4 x LoQ, equivalent to 10 x LoD) includes analyser-specific issues. Additionally, higher ***regulation margin*** is needed to ensure accurate quantification at lower emissions levels than the limit value, considering analyser capabilities, but also measurement uncertainty of other instruments than analysers and reproducibility of whole measurement and data processing phases (schematically, Figure 2-1). This margin should also ensure reliable results at the emission levels defined. The regulation margin between the LoD/LoQ and limit value must have sufficiently wide scope to ensure accurate quantification for development well below the limit value, as well as for certification.

Note that the term 'regulation margin' in this text is a different definition from the "RDE PEMS margin", which is defined as the additional measurement of uncertainty of PEMS compared to the laboratory equipment.

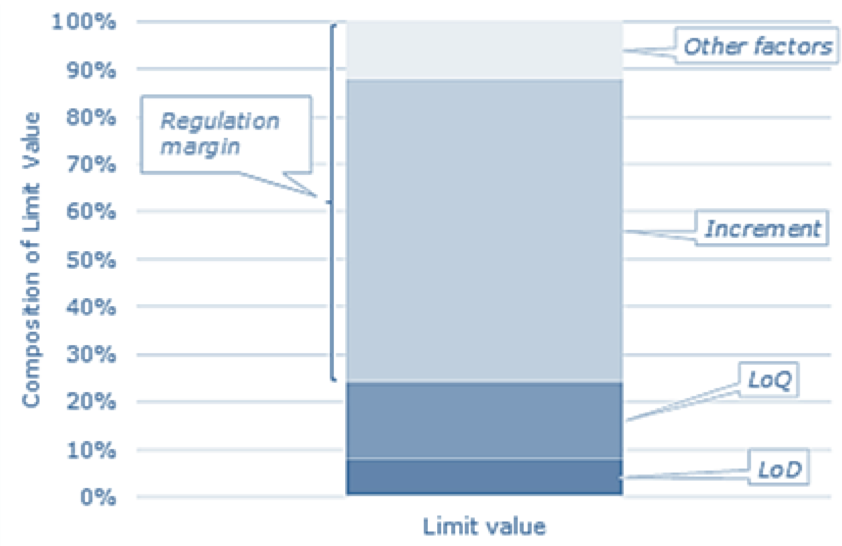

Figure 3-1: Schematic illustration of relationship regulation margin and analyser dependent variability increment relative to limit value. (Figure compiled by authors).

When considering the constituents of regulation margin, some definitions related to capabilities of analysers and measurement uncertainties need to be understood. Commonly, reliably measured concentrations need to be in the working range of analysers, vis-à-vis concentrations between limit of detection (LoD) and the highest calibrated concentration (Figure 3-2). Some definitions are as follows:

- *LoD and LoQ* define the capability of analysers to measure low concentrations. *LoD* is the lowest concentration that can be reliably detected and discriminated from the zero background noise level (typically 3 x the noise level for techniques with continuous recording). LoD is usually defined in ideal conditions that do not represent the real measurement matrix, such as a multi-component exhaust matrix, hence LoD may overestimate the capabilities of analysers. *LoQ* defines the limit, above which the concentrations in the calibrated working area are regarded as quantitative. LoQ is commonly defined as equivalent to 3.3 times LoD.

- *Measurement uncertainty* is defined for total measurement, and it covers all recognised conditions and parameters that affect the result. Measurement uncertainty is limited to a specific set of measurement devices, and specific emission levels (reaches 100% close to LoD). Environmental conditions and interference influences may further increase the uncertainty in a way that cannot be always accounted for. See later in this section for measurement uncertainty of PEMS systems.
- *Reproducibility* describes variation between laboratories. Even with standardised procedures there will be differences in the reproducibility performance e.g., of systems from different manufacturers.

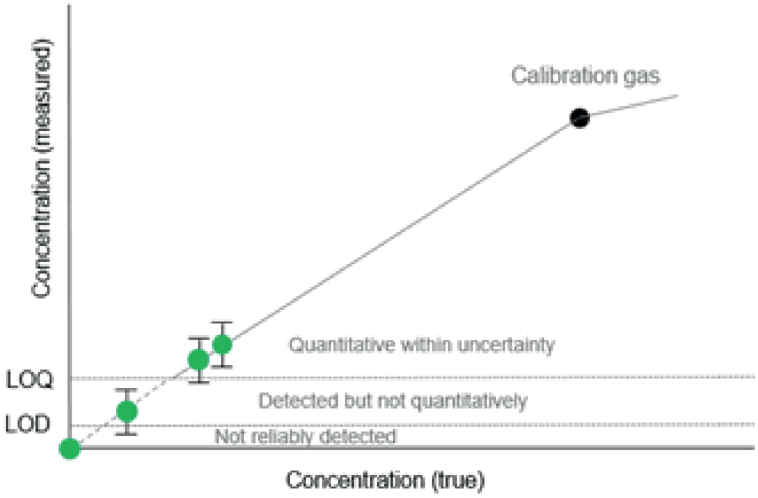

Figure 3-2: Schematic illustration of relationship between limits of detection and quantification and uncertainties of measurement (modified from Eurachem Guide 2014)

LoD concentrations of PEMS analysers used by CLOVE partners were evaluated, and scenarios of LoDs of future PEMS analysers were estimated. LoD concentrations of current PEMS analysers were conservatively defined based on data of traditional PEMS analysers used by CLOVE partners and of new PEMS instruments provided by manufacturers (Table 3-6). These LoD values were set to be similar to or higher than OEM declarations or those determined by the laboratory owning the instrument (e.g., one-minute sec-by-sec on-line measurement). The PEMS future scenario assumes parity with the capabilities of well-established continuous lab-based analysers. Conformity factors (CF) of current RDE procedure are not recommended for inclusion in EURO 7.

Table 3-6: LoD for current, current best and future scenarios of PEMs systems (1)

	NOx/NO_2 ppm	CO ppm	SPN_{10} #/cm^3 raw exhaust	NH_3 ppm	N_2O ppm	CH_4 ppm	HCHO ppm	THC / NMHC/ NMOG ppm	PM µg
LoD, PEMS current	0.7 *	10.0	1000	0.45	0.75	1.00	1.00	1.0	1.5
LoD, PEMS current best	0.7 *	1.0	100	0.40	0.75	1.00	0.60	1.0	1.5
LoD, PEMS future scenario	0.4	1.0	100	0.20	0.15	0.60	0.20	1.0	1.5
Comments on PEMS	Measured using dual CLD or NDUV. Could be measured by QCL or FTIR.	NDIR/PEMS currently poor. Substantial improvement needed (e.g., FTIR).	PN_{10} approaches developed are at the market-ready stage. LOD see note (2).	Already measured on-board using FTIR.	Already measured on-board using FTIR.	Already measured on-board using FTIR.	Already measured on-board using FTIR.	On-board PEMS on market. NMOG could be measured by FID (THC), CH_4 subtracted and HCHO added. In the lab CH_4 cutter or DNPH/HPLC.	PM-PEMS used for HDVs, but not practical for passenger cars. PMP works on measurement procedure.

(1) Some PEMS systems can measure THC/NMHC (and NMOG) as well as PM.
(2) LoD of CPC assumed 1p/cm^3 due to mild contamination of VPR; dilution ratio is typically 100-150, which leads to LoD of 100 #/cm^3 raw exhaust. For DC, LoD is approximately 1000 #/cm^3 raw exhaust and 5000 #/cm^3 the permitted zero level in the regulation.
(*) PEMS current LoD: average of NO 1.1 ppm and NO_2 0.4 ppm.

LoD concentrations of PEMS analysers were converted to mass emissions for different sizes of cars and vehicles to calculate analyser dependent variability increments, which are the recommended minimum emission limits based on PEMS analyser capabilities. Conversions of these concentrations to mass emissions were based on the maximum exhaust flows estimated for each car and vehicle category expected in on-vehicle measurements. The ranges of exhaust flows for car and vehicle categories were based on large databases of emissions tests provided by CLOVE partners. Notably, higher exhaust flows (V_{exh}) for HDVs than for cars lead to higher mass emissions (mg per km or kWh). LoD and LoQ as mass emissions are shown for NOx emissions at LoD of 0.4ppm in Figure 3-3. For small passenger cars, an LoD concentration of 0.7 ppm for NOx leads to LoD of 0.7 mg/km, LoQ of 2.4 mg/km and analyser dependent variability increment of 7.1 mg/km, while for large HDV the respective values are 16, 52 and 156 mg/kWh. At LoD of 0.4 ppm for NOx, respective values for cars are 1.6 mg/km, 5.4 mg/km, 16 mg/km and for HDVs 9 mg/kWh, 30 mg/kWh and 89 mg/kWh. Note: Increment = 3 x LoQ (equivalent to 10xLoD) and LoQ = 3.3xLoD.

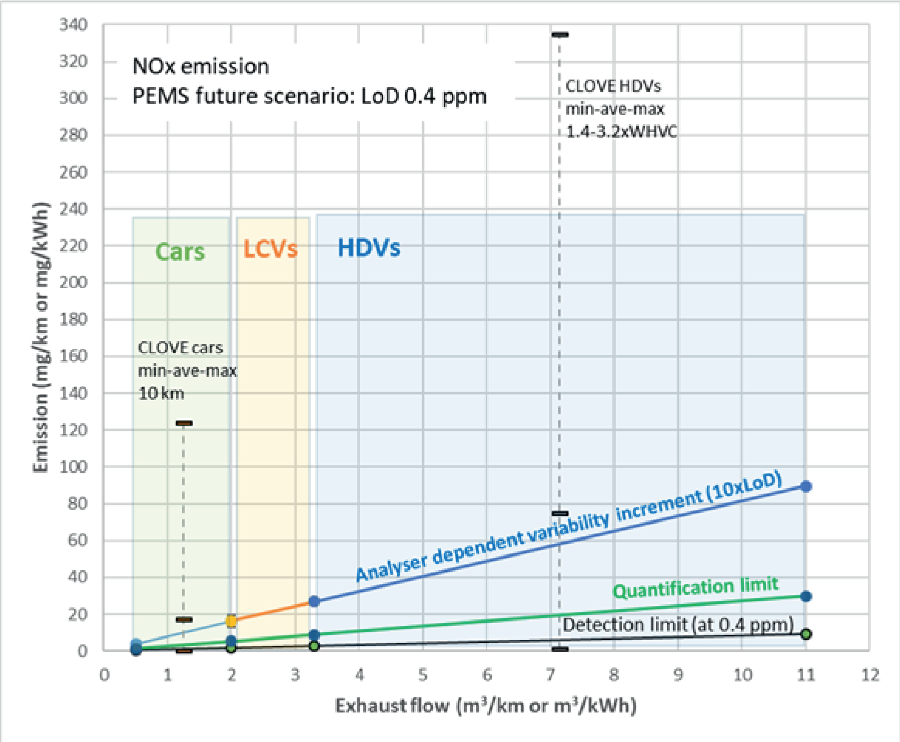

Figure 3-3: LoD, LoQ and analyser dependent variability increment (3xLoQ, 10xLoD) for NOx at analyser at LoD of 0.4 ppm (PEMS future scenario). When converted to mass emissions (mg per km or kWh) these parameters are proportional to exhaust flows from cars and vehicles. Minimum, average and maximum (min-avg-max) values are the results obtained in the CLOVE measurements for Euro 6d cars and Euro VID HDVs.

In Table 3-7, the increments (3xLoQ, 10xLoD) converted to mass emissions are collected for a set of emission species when using current, best and future scenario PEMS systems. The highest exhaust flows estimated for cars, LCVs and HDVs were used in the calculation of mass emissions to establish worst-case requirements. PEMS analyser capabilities are currently modest, hence the increment related to analyser capabilities is high and contributes significantly in regulation margin. However, when analyser capabilities improve, measurement uncertainties and other parameters may become determining for the regulation margin. It is difficult to estimate the increment needed above LoQ to secure reliable results regarding analyser capabilities, so a relatively conservative approach has been taken. The emission limit scenarios presented in Chapters 7 and 8 consider these future PEMS analyser dependent variability increments (Table 3-7).

Table 3-7: Analyser dependent variability increment (i.e., 3xLoQ, 10xLoD) of PEMS analysers converted to mass emissions using the highest exhaust flows estimated for cars, LDVs and HDVs.[a]

	NO_x mg/km mg/kWh	CO mg/km mg/kWh	SPN_{10} #/km #/kWh	NH_3 mg/km mg/kWh	N_2O mg/km mg/kWh	CH_4 mg/km mg/kWh	HCHO mg/km mg/kWh	THC/ NMHC [b] mg/km mg/kWh
Analyser dependent increment converted to mass emissions – PEMS current								
Cars	28	250	3.0×10^{10}	6.8	29	14	27	14
LCVs	47	410	4.9×10^{10}	11	48	23	44	23
HDVs	156	1360	1.6×10^{11}	37	160	78	145	78
Analyser dependent increment converted to mass emissions - PEMS best current								
Cars	28	25	3.0×10^{9}	6.0	29	14	16	14
LCVs	47	41	4.9×10^{9}	10	48	23	26	25
HDVs	156	136	1.6×10^{10}	33	160	78	88	78
Analyser dependent increment converted to mass emissions - PEMS future scenario								
Cars	16	25	3.0×10^{9}	3.0	5.8	8.5	5.3	8.5
LCVs	27	41	4.9×10^{9}	5.0	9.6	14	8.8	14
HDVs	89	136	1.6×10^{10}	17	32	47	29	47

[a]: Exhaust flows (Vexh) of 0.5-2 m^3/km for cars, 2-3.3 m^3/km for LCVs and 3.3-11 m^3/kWh for HDVs (including cold start). Exhaust flows were from CLOVE measurements and large databases of CLOVE partners. These exhaust flows include cold starts, which leads to higher levels than typically reported or estimated based on the average fuel consumption.
[b]: Same or higher LoD than for CH_4 assumed.

PM is not included in this evaluation due to the different measurement principle. It is noted that the PM measurement method is currently used to confirm compliance with the light-duty limit of 4.5 mg/km and heavy-duty engine limit of 10mg/kWh, and the same method would be viable for measuring emissions at 30 – 40% of these levels (~2 mg/km LD and ~4 mg/kWh HD). The measurement system cost of this change would be minimal.

Measurements with current PEMS systems are addressed with higher uncertainties than those for standard laboratory equipment. The uncertainty of measurement includes the accuracy of the analysers and many other parameters, for example exhaust flow, distance and time alignment as evidenced by JRC (Giechaskiel B., 2018). Additionally, sampling is a source of uncertainty related to e.g., condensation risks of species or reactions in pre-treatment for extractive sampling. The contributing parameters to uncertainty of on-vehicle measurements can be categorised as:

- Emission concentration (ppm) resulted from: Analyser accuracy, Gas bottle accuracy, Analyser linearity, Span drift, zero drift, Worse-case drift
- Exhaust mass flow (kg/s) resulted from: EFM accuracy, EFM drift, EFM linearity

- Covered distance (km) resulted from: GPS signal
- Additional parameters: Time alignment and response time (dynamics), Boundary (environmental) conditions (on instrumentation accuracy), interference and conversion efficiencies, CVS bag measurement (subtracted)

In the latest JRC study (Giechaskiel B., 2021) zero drift of PEMS gas analysers, an important source of uncertainty, was found to be below 3 ppm for NOx, supporting the potential lowering of the uncertainty. In the CLOVE testing, PEMS showed additional hurdles, e.g., erroneous CO baseline and deterioration of NDUV (NOx).

Different scenarios were calculated for the current and future PEMS equipment based on the latest assessment of PEMS measurement uncertainty by JRC.

- Scenarios 1 and 2 (with 3 ppm drift and correcting for zero drift): Current and future PEMS measuring at levels close to current emission limits respectively.
- Scenarios 3 and 4 (with 3 ppm drift and correcting for zero drift): Current and future PEMS measuring at a possible scenario for EURO 7 limit (e.g., 20mg/km for NOx) respectively.

Table 3-8: Measurement uncertainty with current PEMS for cars(a)

Parameter	Current uncertainty	Future uncertainty[b]	Current uncertainty	Future uncertainty[b]
NOx	at 80mg/km		at 20mg/km	
	±23% (±18 mg/km)	±10% (±8 mg/km)	±81% (±16 mg/km)	±13% (±3 mg/km)
CO	at 500mg/km		at 200mg/km	
	±33% (±164 mg/km)	±10% (±50 mg/km)	±79% (±159 mg/km)	±14% (±28 mg/km)
THC	at 100mg/km		at 50mg/km	
	±15% (±15 mg/km)	±10% (±10 mg/km)	±26% (±13 mg/km)	±14% (±7 mg/km)

[a]: Uncertainties as mg/km are higher for HDVs than for cars due to differences in their exhaust flows.

[b]: With zero drift=0 mg/km

Table 3-8 analyses the measurement uncertainties for the aforementioned scenarios for NOx, CO and THC emissions. The current uncertainty is used for the assessment of the margin for PEMS devices in the RDE legislation and the definition of the conformity factors. As it can be seen for all species, the uncertainty is high (±23% for NOx). The future uncertainty is considered closer to the actual performance of current PEMS and in this case the NOx uncertainty is significantly reduced (±10%) due to lower zero drift. Lower limit values at EURO 7 will significantly affect the performance of the equipment due to the lower accuracy of the analyser at very low emission levels and the relatively high zero drift. Even though there is no final input from PEMS suppliers regarding the feasibility of the values presented in the final scenario, the best equipment is expected to be able to minimise the zero drift which will result in uncertainty of ±13 to 14%. While CEN (the European

Committee for Standardization)is working in detail on uncertainties of PEMS (CEN, 2021) 15% uncertainty (40% for PN) was considered when developing the recommended limits. However, since analyser capabilities to measure low concentrations and measurement uncertainties are different aspect (examples are presented below the Table), measurement uncertainties need to be evaluated in the implementation regulation.

The recommended minimum emission limits (Table 3-7) and measurement uncertainties (Table 3-8) illustrate different viewpoints. The recommended minimum emission limit is a part of limit setting procedure, while measurement uncertainty is related to a single emission result obtained with specific instruments used in laboratory. The following examples illustrate these differences for NOx and CO emissions:

a) The recommended minimum emission limit for NOx is 16 mg/km, so the limit value should not be lower than that but could be much higher for many reasons (including technology availability). / Uncertainty: A laboratory measures NOx emission and achieves a result of 20 mg/km, which is above detection limit and quantifiable. If measurement uncertainty with instruments used is ±3 mg/km, the result could be reported as 20 mg/km ±3 mg/km.
b) The recommended minimum emission limit for NOx is 16 mg/km, so the limit value should not be lower than that but could be much higher for many reasons (including technology availability). / Uncertainty: A laboratory measures NOx emission and achieves a result of 10 mg/km, which is above detection limit (corresponding to e.g., 1.6 mg/km) and quantifiable. If measurement uncertainty with instruments used is ±1.3 mg/km, the result could be reported as 10 mg/km ±1.3 mg/km.
c) The recommended minimum emission limit for CO is 25 mg/km. Limit value should not be lower than that but could be much higher for many reasons. / A laboratory measures CO emission and achieves a result of 200 mg/km. If measurement uncertainty with instruments used is ±28 mg/km, the result could be reported as 200 mg/km ±28 mg/km.

Implementation regulation is assumed to define criteria for evaluating the compliance with the limits in relation to the measured value.

3.6 PEMS requirements- initial recommendations

Overall, many advances are possible to enable improved capability of PEMS to reliably analyse low emission levels. These include a) further requirements for PEMS analysers (e.g., suitable measurement ranges) and quality of calibration and zero gases; b) data processing of instantaneous concentrations close to or below detection limits of analysers; c) evaluations of measurement uncertainties of the whole PEMS systems and improving critical parts; d) validation and verification of PEMS systems.

For clean cars and vehicles, emission concentrations are increasingly at very low levels, close to, or below, the LoD, and thus cannot be reliably analysed over a large part of test duration. Even if the true concentration was zero, the analyser records values cumulatively increasing the bias in the result (as in current procedure EU 2017/1151). This potential artefact can be softened by using post-processing of data, for example, replacing values below LoD by zero, or dividing them by a constant. For EURO 7, the procedure of post-processing of data below LoD is recommended.

The issue of drift of PEMS analysers is known and can be tackled by many means, e.g., by selecting analysers and calibration gases; correcting for drift is already included in heavy-duty regulation. However, drift is a different topic than biased baseline, which could be due to e.g., using insufficient quality of zero gas or very high concentration of calibration gas. A baseline may be biased at the start of the test, but this will not be detected by monitoring the drift (drift is relative to the concentration at the start of test).

Additionally, requirements are recommended for OEM validation of PEMS and periodic comparisons to laboratory measurements (e.g., annually or every 6 months). Validation tests of PEMS should also include the sensitivity against real world test conditions, such as accelerations and variations of ambient pressure and temperature. However, these are only examples to point out the need for consideration of a wide set of requirements when implementation of regulation is discussed.

4 Euro 6d and d-temp emissions performance – LDV

4.1 Preliminary evaluation of the technical effectiveness of Euro 6 testing requirements

The latest LDV Euro 6 standard, being adopted in different phases over the period 2012-2022, along with the Euro VI standards for HDV brought more stringent requirements in vehicle emission control in the EU. In this ten-year period, following several regulatory amendments, it incorporated key developments in approaching the standards, such as real driving emissions (RDE) testing as an essential part for certification (LDV) and compliance (LDV and HDV) testing and monitoring. Notably, the 4th package of RDE (as stipulated in Regulation (EU) 2018/1832) is a comprehensive regulatory component that covers a wide area of vehicle operation and simplifies evaluation of results.

However, a point of further consideration is whether the latest specifications of RDE testing are (and whether they need to be) all-inclusive of operation conditions on the road, and whether there are specific operation conditions that still escape regulatory control (e.g., low speeds including prolonged stop-and-go operation). Overall, there has been a shift in EU emission standards from laboratory-based testing towards on-road testing under realistic driving conditions. However, laboratory testing still remains the only option for specific type approval (TA) tests (e.g., Type 6 test). Therefore, an additional point of discussion is whether some (or all) of remaining laboratory testing can be included within an extended RDE framework.

4.1.1 Current status

The New European Driving Cycle (NEDC) test was replaced in 2017 by the newer Worldwide Harmonised Light Vehicles Test Procedure (WLTP). The related test cycle, i.e., the Worldwide Harmonised Light Vehicles Test Cycle (WLTC) is designed to reflect more accurately “real-world” driving conditions, which was flagged as an issue for measuring emissions of pollutants such as NOx. All new LDV registrations have been subject to compliance with the same limits as with the NEDC from 1st September 2018 (and a year earlier for new types of vehicles). The applicable limits for compliance at TA stage are summarised in Annex 1: Summary of Euro 6/VI emission standards. It is stressed that emission limits were kept unchanged from NEDC (length 10.9 km) to WLTC (length 23.3 km).

Another notable change to LDV testing was the introduction of the Real Driving Emissions (RDE) test, to measure emissions on the road. As part of the RDE test, vehicles are fitted with a PEMS, which must measure CO_2, CO, PN and NOx, with the last two species subject to regulatory control. Emissions under RDE are specified using a “conformity factor” (CF) aimed to cover the difference in performance of the PEMS equipment against the lab ones. The applicable CFs were revised under Euro 6d, which came into effect for new type approvals from 1st January 2020 and applied to all new vehicle registrations from 1st January 2021. Under Euro 6d the NOx CF drops to 1.43 (1 plus a 0.43 additive factor). A conformity factor of 1.5 is required for PN, i.e., comprising the limit factor (1.0) and a margin of a further 50% to account for instrument accuracy during testing in the real-world environment. The margins for PEMS performance currently being under continuous review. In fact, a recent JRC report (JRC, 2021), based on 2020 PEMS data and scientific evidence, suggested that the NOx margin can be further reduced to 0.23 (CF=1.23) and the PN margin to 0.34 (CF=1.34). This is mainly due to the improved performance of state-of-the-art PEMS in terms of NOx zero drift and improvement of the exhaust flow meter’s uncertainty.

4.1.2 Assessment

Figure 4-1 shows the evolution of hot NOx and PN emission factors for petrol, diesel, and CNG passenger cars from Euro 0 to Euro 6d emission standards, as derived by the Handbook Emission Factors HBEFA 4.1. Focusing on NOx emissions of diesel cars (upper panel of Figure 4-1), hot emission levels remained between around 750 mg/km and 1,000 mg/km from Euro 0 to Euro 5, while a significant decrease is detected from Euro 6c and then again from Euro 6d-temp onwards, latterly with an average hot emission factor of 44 mg/km. In addition, this analysis shows that the gap in emission factors between diesel and petrol vehicles is almost eliminated in Euro 6d and Euro 6d-temp vehicles.

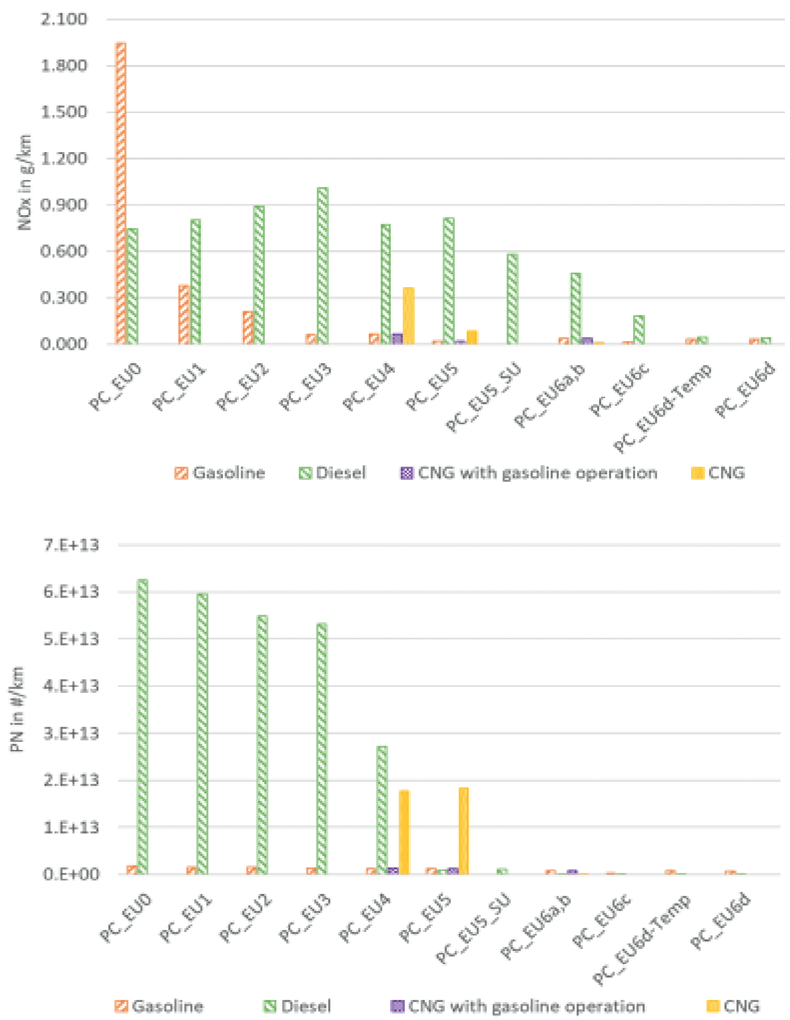

Figure 4-1: Average hot NOx (upper) and PN (lower) emission factors for Euro 0 to Euro 6 passenger cars from HBEFA 4.1 (German traffic situation mix)[6]

The lower panel of Figure 4-1 reveals that the introduction of the Euro 5 emission standard brought a significant reduction of diesel vehicles PN emissions, due to the installation of diesel particulate filters on all new vehicles. The improvement of DPF filtration efficiency brought further reductions of PN emission factors in Euro 6. Compared to Euro 3 non-DPF vehicles, a reduction of 99.95% is observed in the hot PN emission factor of Euro 6 diesel vehicles.

[6] It is based on emission tests on hundreds of passenger cars in real world cycles for the Handbook Emission Factors (HBEFA 4.1, http://www.hbefa.net).

One may argue that despite the latest regulatory provisions (Euro 6 standards, RDE regulation) TA testing may still be conducted based on rather a limited range of real-world boundary/driving conditions. Of particular interest are short trips which are characteristic of European driving behaviour. Figure 4-2 exemplarily shows measured cumulated emissions of a petrol passenger car in the first part of a moderate RDE cycle that is compliant with current regulation. In addition to the emission values, the speed profile as well as the vehicle distance travelled are depicted in the bottom diagram. It can be seen that a large part of the overall emissions is accumulated during the initial seconds after the engine has started. Once the catalyst has reached its operating temperature and catalyst heating mode is deactivated the further emission increase occurs at a much slower pace, at least for some of the pollutants.

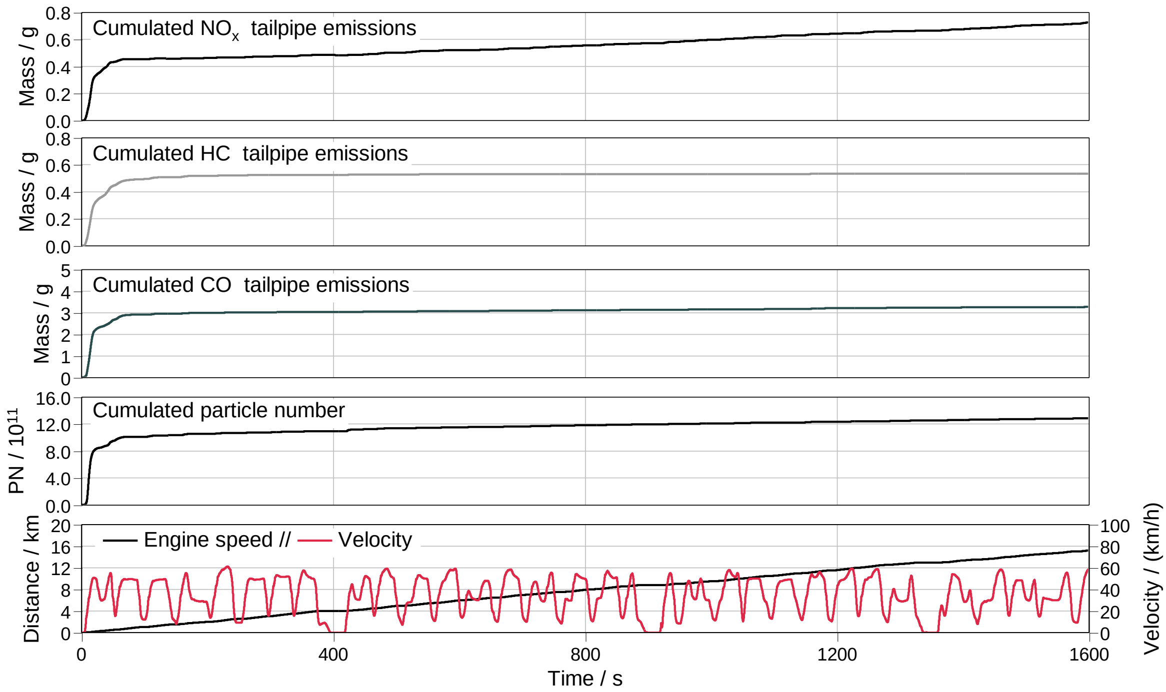

Figure 4-2: Cumulated emissions for a state-of-the-art petrol engine in a moderate RDE cycle (source: CLOVE own data)

Euro 6 also introduced more robust provisions regarding DPF-regenerating events. As a notable example, in a relevant JRC study (Valverde, V., Giechaskiel, B., 2020), PN and NOx emissions of a Euro 6d-temp diesel vehicle that was tested were compliant with all applicable emission limits both in the laboratory and on the road (WLTP 23 °C and RDE-compliant tests). More significantly, in the testing exercise, six regeneration events took place (1300 km driven in total with an average distance between regeneration events of 200 km). During the regeneration events, the laboratory limits for PN and NOx (although not applicable) were exceeded in one of the two measured regeneration events. However, the on-road emissions were below the applicable not-to-exceed limits when regenerations occurred.

The current LDV testing is based on WLTC testing on chassis dyno test benches and on RDE emission tests performed on the road with PEMS equipment. Beside these two tests, further lab/chassis dyno-based tests are required including low temperature test (Type 6) for petrol engines or evaporation test (Type 4). In the following section, WLTC and RDE emissions testing procedures are analysed, and certain weak points are identified.

Chassis-dyno testing (WLTC)

The WLTC is a chassis dyno cycle, which was introduced with the intention of covering a representative and much larger proportion of normal driving conditions than NEDC. With the WLTC, the measured CO_2 emission/fuel consumption and air pollutant values of different vehicles from different manufacturers can be compared with one another, under the same reproducible conditions. This allows the robust setting of CO_2 emission targets. However, the WLTC, as utilised during TA and in-use compliance (IUC) testing today, still has some limitations and drawbacks:

- The WLTC cycle follows a pre-defined vehicle speed profile which may allow the optimisation of the vehicle's emission control systems specifically for these test conditions, including specifically trained vehicle control strategies.
- The WLTC cycle covers moderate driving, which is only a limited subset of all possible driving conditions that the vehicle may encounter in real life operation. In addition, there is no distinction made between different vehicle applications, e.g., in-use conditions of vans compared to those of a sports car. Overall, driving scenarios and operating conditions, such as short trips, low load driving, trailer towing are not covered by the WLTC.

As a result, the WLTC can be considered a less 'realistic' test compared to RDE testing conditions within the current Euro 6d legislation (RDE package 4). The emission values detected in the WLTC are in most cases lower than those occurring in RDE driving cycles, as exemplarily illustrated for a modern GDI engine in Figure 4-3. RDE#1 and #2 are fully compliant with RDE regulation (RDE#1 comprises several harsh acceleration and deceleration events, with driving dynamics being just at the RDE boundaries), while RDE#3 is a non-compliant RDE test but only in terms of trip duration, which is smaller than the one prescribed by the regulation. As shown in this graph, in different RDE scenarios the average over emissions compared to WLTC emissions can reach up to 5 times the values detected in the WLTC for certain species (in this particular example of a petrol GDI vehicle, CO and PN).

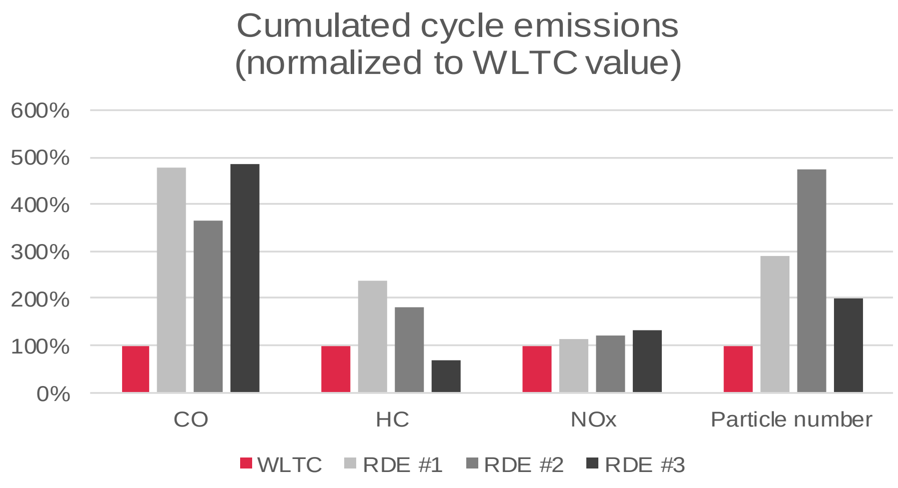

Figure 4-3: Comparison of tailpipe emissions between WLTC and different RDE cycles of a state-of-the-art petrol GDI (selected example) (source: CLOVE own data)

RDE testing

To overcome some of the WLTC testing weak points, on road (RDE) testing with PEMS equipment was introduced. With this approach the issue of the pre-known cycle, fixed test conditions, and the mismatching of chassis-dyno testing and on-road testing has improved significantly. Also, the regulated driving conditions are vastly extended with the current RDE regulation compared to using only the WLTC. The benefits of the introduction of RDE emission tests can be seen when looking at a comparison of Euro 6d-temp/6d RDE compliant vehicles and vehicles of prior emission standards (AECC, 2021).

The current RDE legislation has forced emission control systems to be designed for more challenging RDE-based testing requirements. The WLTC is no longer the main target when it comes to compliance because real-world RDE cycles are much more challenging and representative. However, for LDVs in particular, there are still certain key weak points of the current procedure. In terms of pollutant coverage not all emission species are covered in the RDE tests (e.g., THC, CO). At the same time, not all boundary conditions (e.g., uphill driving, severe cold ambient conditions) and driving/operating conditions (e.g., short trips under 10km, extended stoppage periods) are covered by current RDE legislation. More details on the real-world emission performance (i.e., within and beyond current RDE) of state-of-the-art vehicles today are provided in section 4.2.

In principle, the framework to extend the RDE to cover additional operation/driving conditions and potentially include other emissions species (apart from NOx and PN), is in place. Moreover, RDE made it clear that taking good emission performance in all normal life use can be a useful criterion to simplify regulation, and potentially remove existing distinctions, differentiations, and exceptions.

4.2 Findings on tailpipe emissions (LDVs) based on emissions database

To better assess the emissions performance of the current vehicles/technologies, an emissions database was created (Step 1 of the methodology outlined in Chapter 2). This database includes measurement data from CLOVE partners (both from testing activity within the current framework contract and from own data) as well as from JRC and stakeholders. A detailed description of the vehicles included, the species, and test conditions evaluated is presented in Annex 2 of this report. The main findings of this analysis are presented in the following sub-sections, which practically constitute Step 2 of the methodology presented in Chapter 2. As a first step, the emissions performance (currently regulated species) of latest Euro 6d and 6d-temp vehicles within and outside the RDE boundaries is presented, while emission levels of the currently non-regulated pollutants (lab tests) are presented in a separate sub-section. Finally, the testing conditions that are associated with emission excursions (for both regulated and non-regulated species) are presented in the last sub-section.

4.2.1 Emissions performance within current RDE boundaries

Figure 4-4 to Figure 4-12 present the NOx, SPN_{23} [7] and CO emission performance of the Euro 6d and 6d-temp vehicles included in the CLOVE database when tested within the current RDE boundaries (e.g. in terms of trip dynamics and trip characteristics, ambient temperature and altitude, positive elevation gain). Each figure includes test data separated

[7] SPN_{10} emission measurement data were also available, but only for some vehicles, mainly those tested by CLOVE in the context of the current study. Thus, it was decided that the PN emission performance of the current vehicles is based on SPN_{23} data, while as presented in chapter 7, EURO 7 recommendations refer to SPN_{10} emissions.

as urban, rural, motorway and total trip, for all the different powertrain technologies as further described in Annex 2, while Euro 6d vehicles are also presented in a separate graph as they represent the very latest technology step in the market. Emission levels presented in these graphs were calculated without any correction prescribed in RDE regulation (e.g., correction factor based on CO_2 emissions) as the target of this exercise is to evaluate the absolute emission levels of current vehicles and identify potential weaknesses in emission performance. In each case, the lowest limit (irrespective of the powertrain type e.g., there is currently no PN emission limit for PFI engines) of the current regulation without any conformity factor is presented for comparison reasons. This comparison is further quantified in the corresponding distribution plots (e.g., Figure 4-5), which show the emission levels distribution of all tests within RDE boundaries from all vehicles for each pollutant. The cumulative share of tests is also included in the same graph providing information about the percentage of tests that are, for example, below the lowest current limit or half the limit. Finally, additional statistical data (e.g., average values, standard deviation median) for each powertrain type are presented in section 2.1.2 of Annex 2.

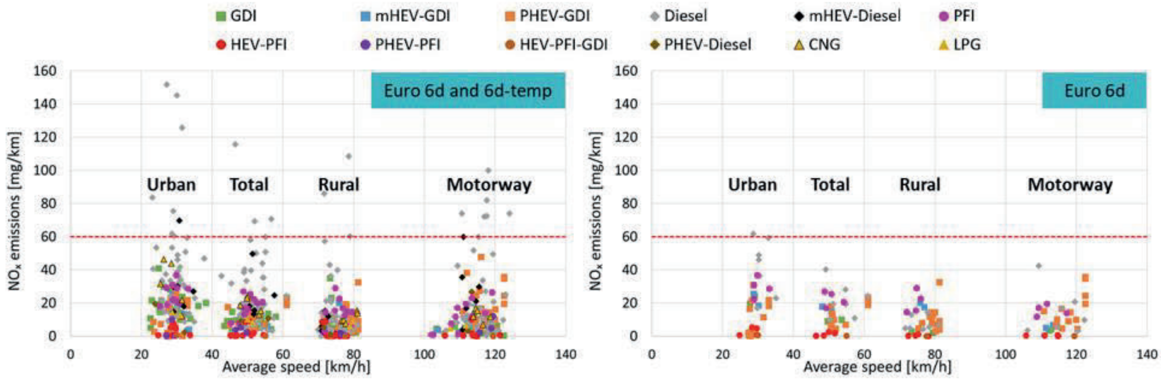

Figure 4-4: NOx emissions for each powertrain type over trips within current RDE boundaries. Note: Emission levels and limit do not include any correction (e.g., CO_2-based) or conformity. factor

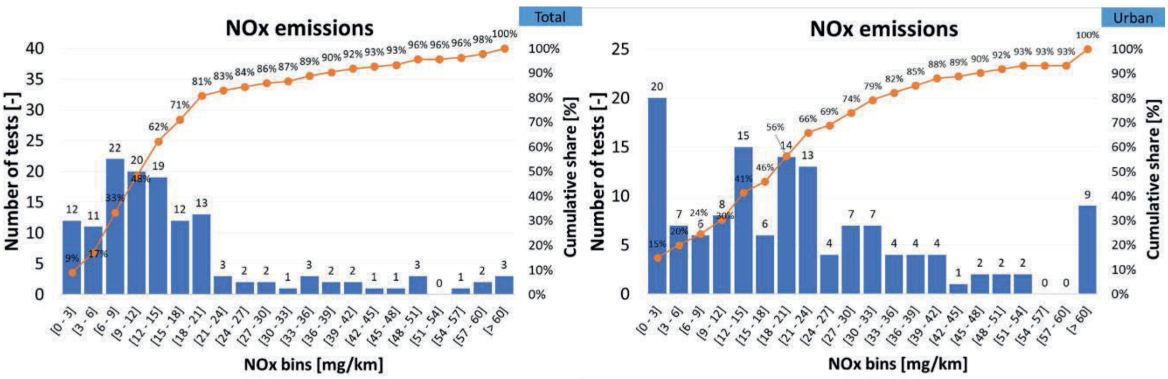

Figure 4-5: NOx emissions performance distribution of all tests (within RDE boundaries) of Euro 6d and 6d-temp vehicles.

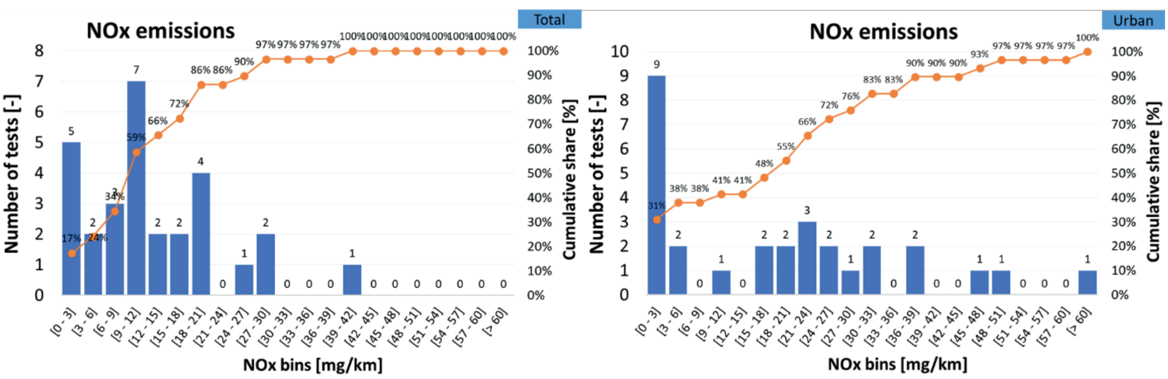

Figure 4-6: NOx emissions performance distribution of all tests (within RDE boundaries) of Euro 6d vehicles only.

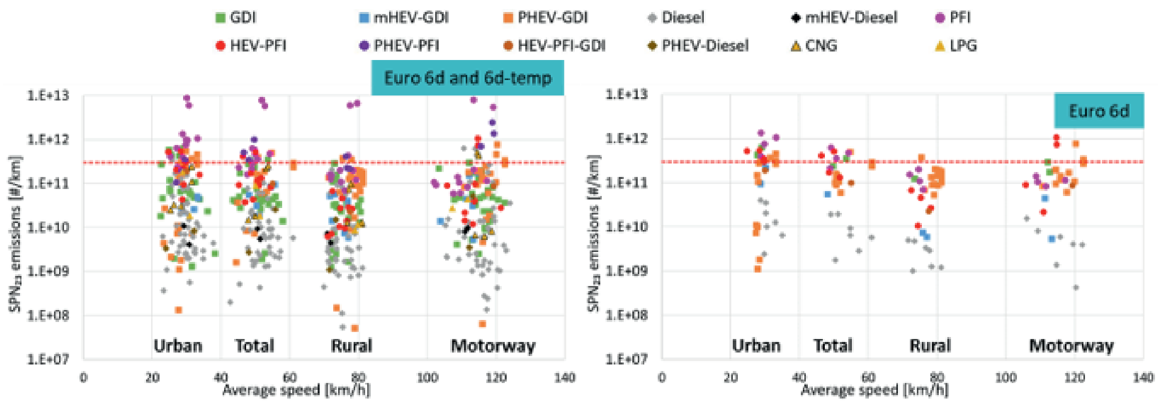

Figure 4-7: SPN_{23} emissions for each powertrain type over trips within current RDE boundaries. Note 1: Emission levels and limit do not include any correction (e.g., CO_2-based) or conformity factor. Note 2: The presented limit is not currently applicable on PFI engines.

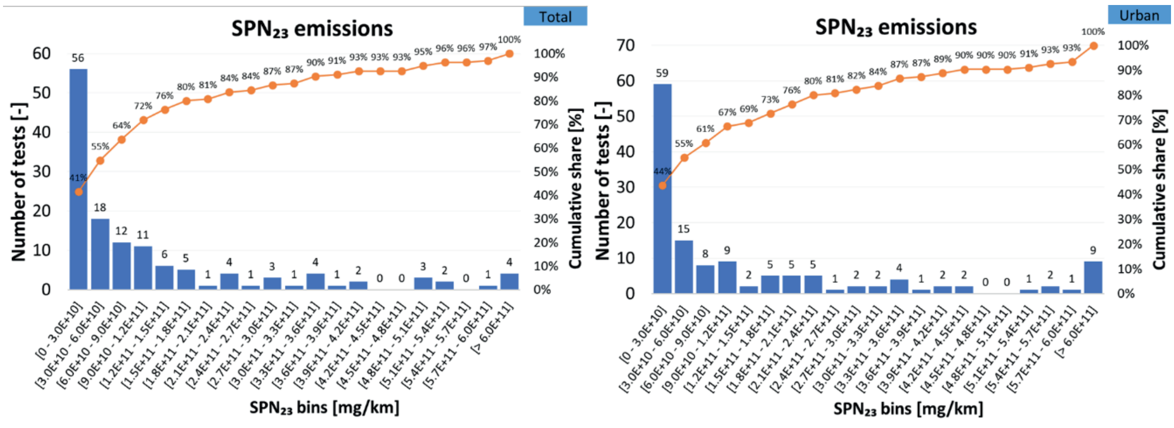

Figure 4-8: SPN_{23} emissions performance distribution of all tests (within RDE boundaries) of Euro 6d and 6d-temp vehicles.

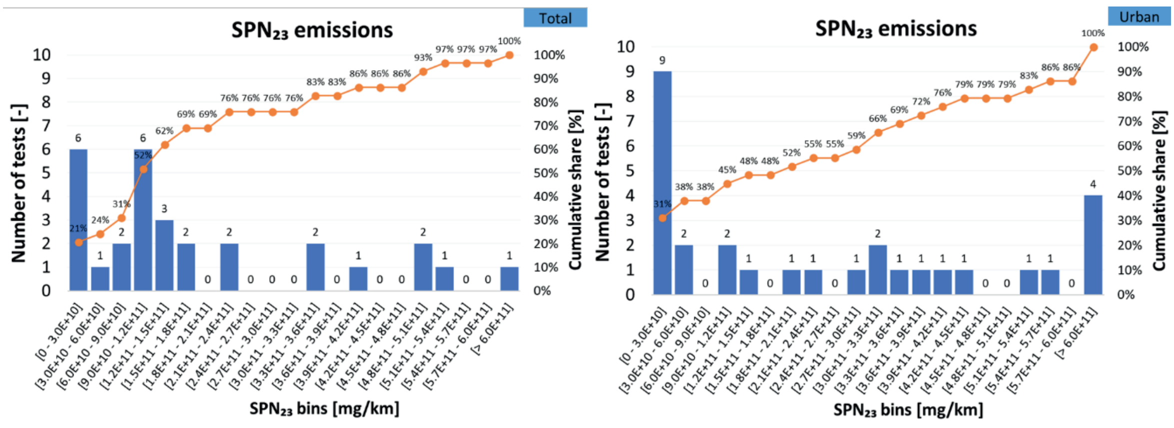

Figure 4-9: SPN_{23} emissions performance distribution of all tests (within RDE boundaries) of Euro 6d vehicles only.

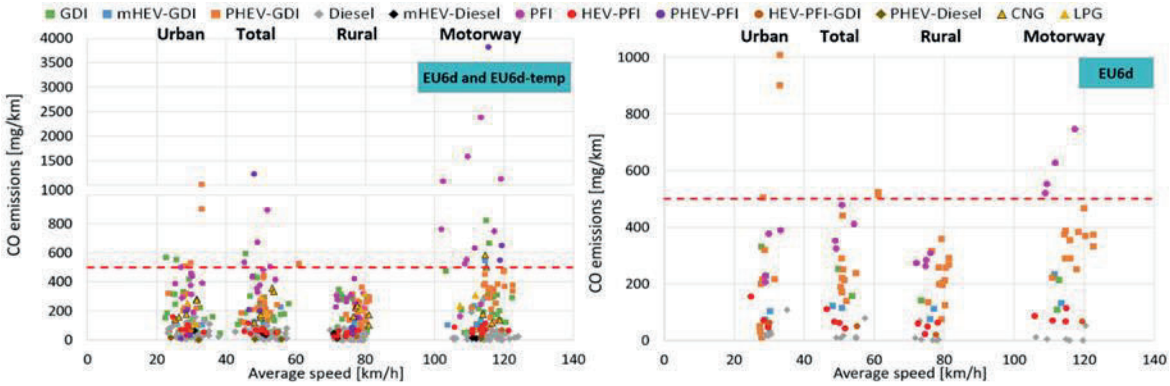

Figure 4-10: CO emissions for each powertrain type over trips within current RDE boundaries. Note 1: Emission levels and limit do not include any correction (e.g., CO_2-based) or conformity factor. Note 2: no CO limit is currently applicable on RDE tests.

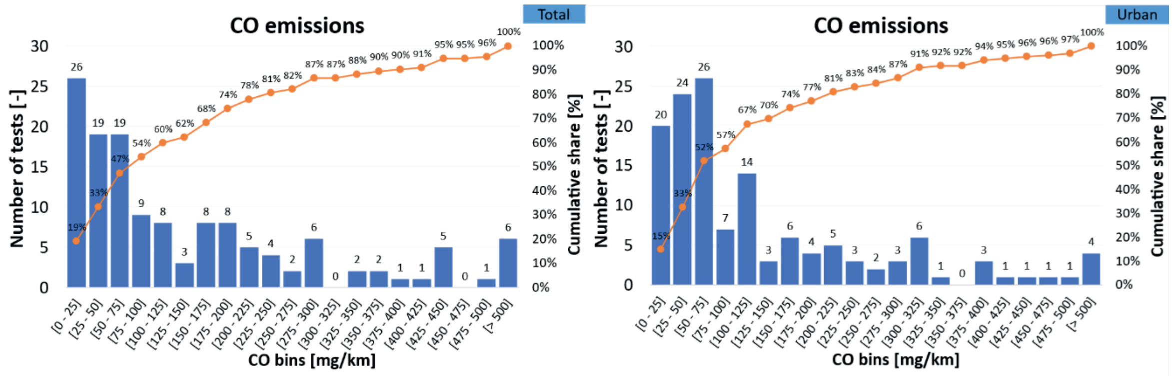

Figure 4-11: CO emissions performance distribution of all tests (within RDE boundaries) of Euro 6d and 6d-temp vehicles.

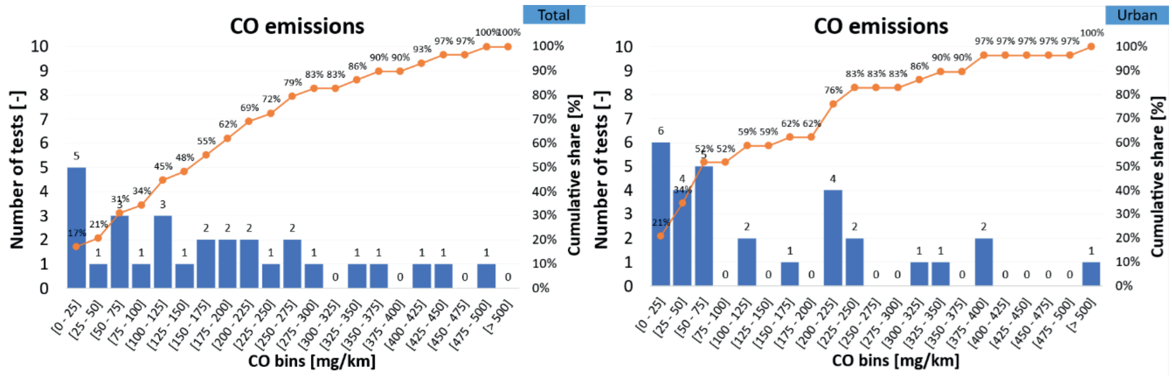

Figure 4-12: CO emissions performance distribution of all tests (within RDE boundaries) of Euro 6d vehicles only.

Results show that emission levels of both Euro 6d and 6d-temp vehicles are at very low levels when tested within the current RDE boundaries. The majority of tests are below half of the strictest current limit as shown by the distribution plots. As regards the emission performance of the different powertrain technologies, diesel vehicles are at the upper end of NOx emission levels, although most of these cases correspond to Euro 6d-temp vehicles rather than Euro 6d. High SPN_{23} emissions were observed in most PFI petrol vehicles (currently not subject to PN limits, thus not equipped with particulate filters), exceeding the 6×10^{11} p/km limit that applies to DI petrol and diesel vehicles by more than one order of magnitude in the case of a few Euro 6d-temp vehicles. CO emissions are in almost all cases at low levels (with the exception of some petrol vehicles), revealing that lambda control is effective when vehicles are tested within the current RDE conditions. As regards the comparison between Euro 6d and 6d-temp vehicles, there is a decreasing trend in the emission levels of the former, although this can be attributed to the different sample of vehicles (19 Euro 6d and 52 Euro 6d-temp).

4.2.2 Emissions performance beyond current RDE boundaries

Figure 4-13 to Figure 4-21 presents the NOx, SPN_{23} [8] and CO emission performance of the CLOVE database vehicles when tested beyond the current RDE boundaries. The non-compliance reasons refer mainly to high driving dynamics (high v×a), trip composition different than the one prescribed in the regulation (i.e., share of urban, rural, motorway phases), high positive elevation gain, low ambient temperature, and test with DPF regeneration. As in the previous section, emission levels are presented separately for urban, rural and motorway phases as well as the total trip. The different trip phases are not clearly distinguished because trip characteristics and composition vary greatly in terms of urban, rural, motorway share and average vehicle speed in tests these tests (beyond RDE boundaries). The presented emission levels were calculated without any correction for extended conditions or based on CO_2 emissions. As in the previous sub-section, the emission levels distribution and cumulative share of all tests from all vehicles are presented for each pollutant.

The results on the tests beyond the current RDE reveal that in both Euro 6d and Euro 6d-temp there is a clear increase of emissions compared to the tests within the RDE boundaries, although it can be observed that in most cases higher emitters correspond mainly to Euro 6d-temp vehicles. The observed emission excursions can be related to specific events and driving conditions, as further analysed in section 4.2.4. Focusing on NOx emissions, it can be observed that driving conditions beyond the RDE boundaries are challenging mainly for diesel vehicles, while CO emissions excursions are observed in petrol vehicles, mainly GDI. Finally, as regards SPN_{23} emissions, petrol PFI vehicles remain at high levels, while these conditions are also challenging for some GDI vehicles (with GPF) and diesel vehicles during DPF regeneration, revealing that periods with low filtration efficiency of particulate filters can significantly increase tailpipe emission levels. This topic is further discussed in section 4.2.4. Despite the above-mentioned emission excursions, a worth-mentioning observation from this analysis is that more than half of the tests beyond RDE boundaries are already below half of the strictest current limit. This is an indication that current vehicles are designed to cover conditions both within and beyond RDE boundaries, at least to some degree.

[8] SPN_{10} emission measurement data were also available, but only for some vehicles, mainly those tested by CLOVE in the context of the current study. Thus, it was decided that the PN emission performance of the current vehicles is based on SPN_{23} data, while as presented in chapter 7, EURO 7 recommendations refer to SPN_{10} emissions.

5.

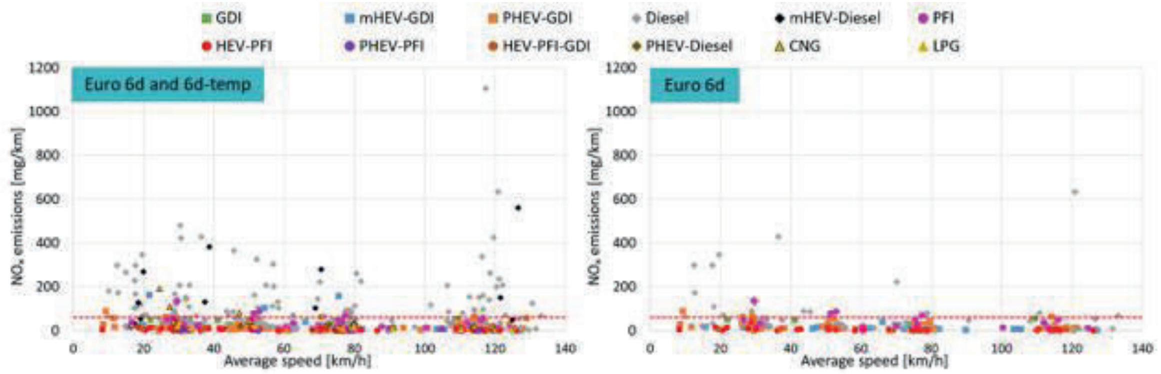

Figure 4-13: NOx emissions for each powertrain type over trips beyond current RDE boundaries. Note: Emission levels and limit do not include correction (e.g., CO_2-based or due to extended conditions) or conformity factor.

6.

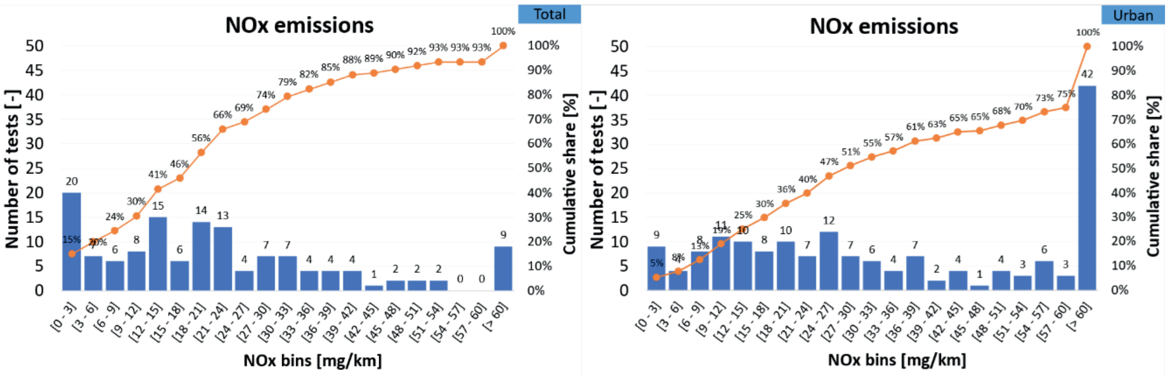

Figure 4-14: NOx emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d and 6d-temp vehicles

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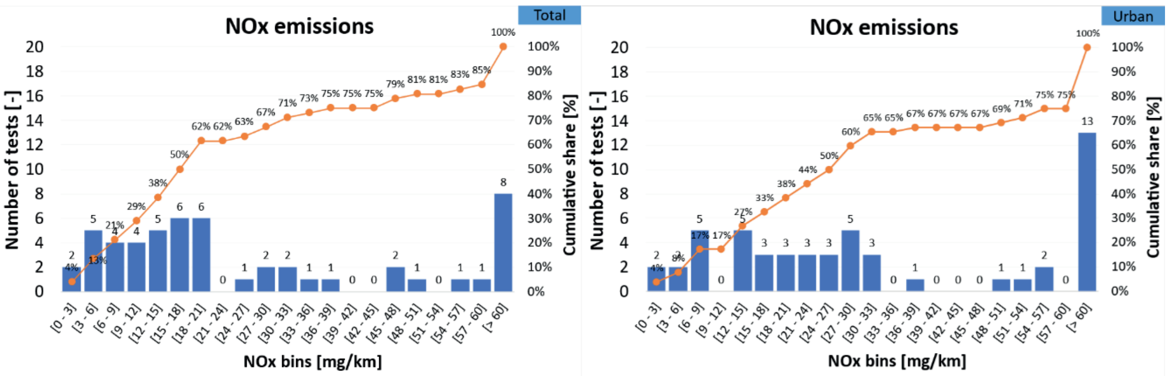

Figure 4-15: NOx emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d vehicles only

8.

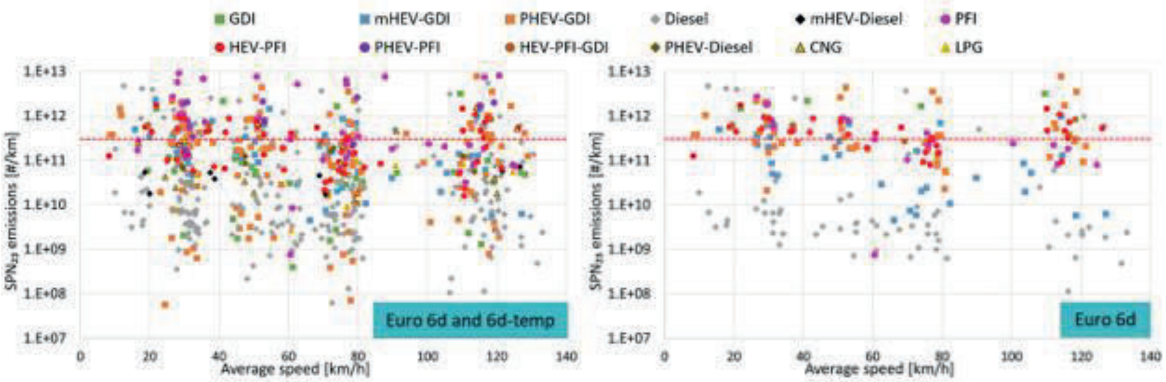

Figure 4-16: SPN_{23} emissions for each powertrain type over trips beyond current RDE boundaries. Note 1: Emission levels and limit do not include any correction (e.g., CO_2-based or due to extended conditions) or conformity factor. Note 2: The presented limit is not currently applicable on PFI engines.

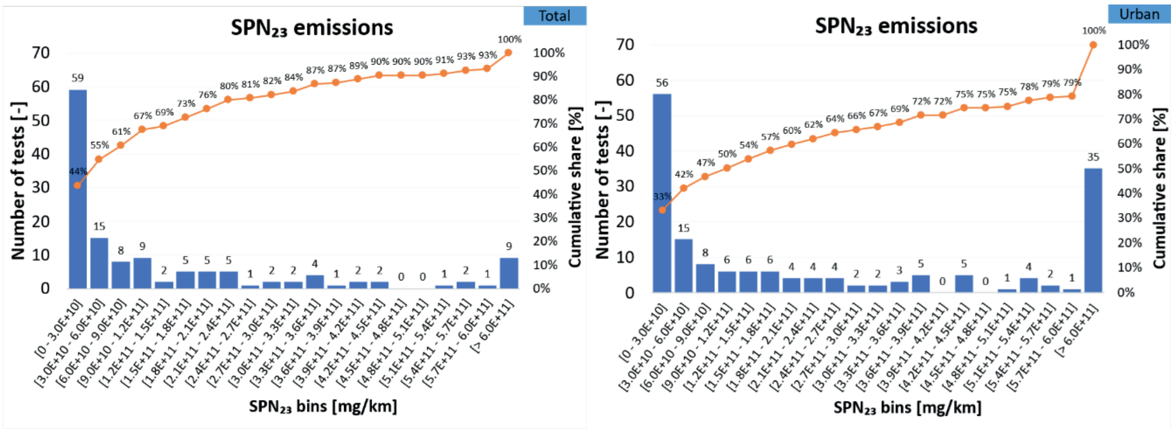

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Figure 4-17: SPN$_{23}$ emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d and 6d-temp vehicles

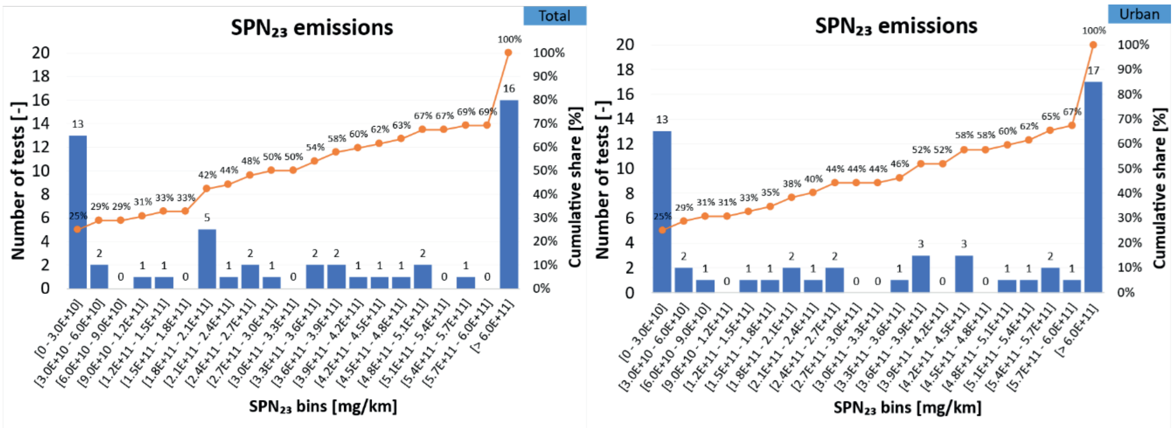

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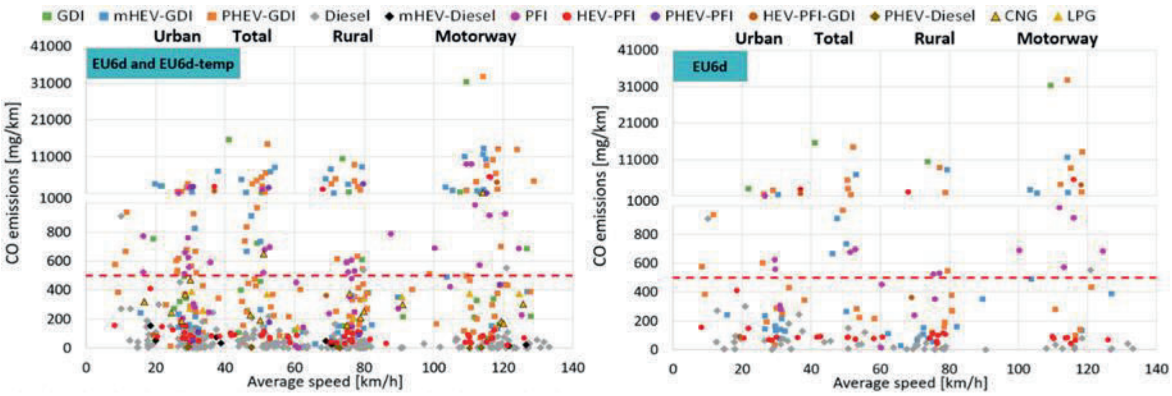
Figure 4-18: SPN$_{23}$ emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d vehicles only



11.

Figure 4-19: CO emissions for each powertrain type over trips beyond current RDE boundaries. Note 1: Emission levels and limit do not include any correction (e.g., CO_2-based or due to extended conditions) or conformity factor. Note 2: no CO limit is currently applicable on RDE tests.

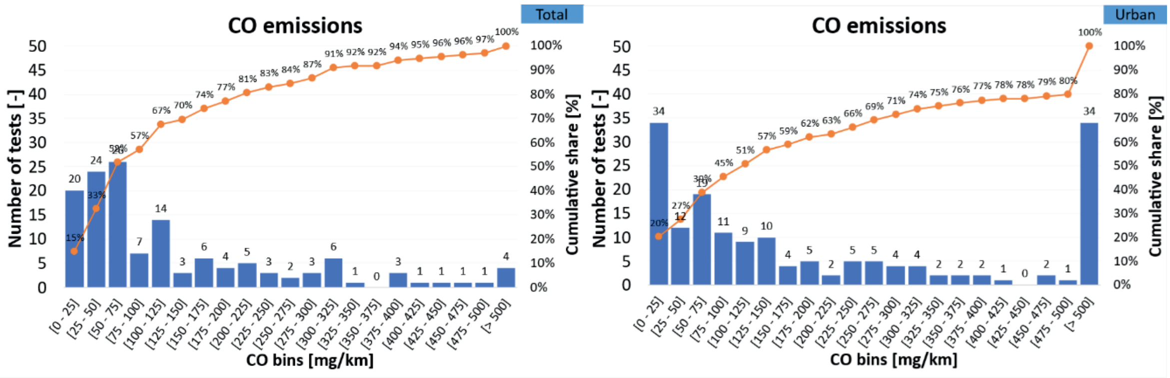


Figure 4-20: CO emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d and 6d-temp vehicles

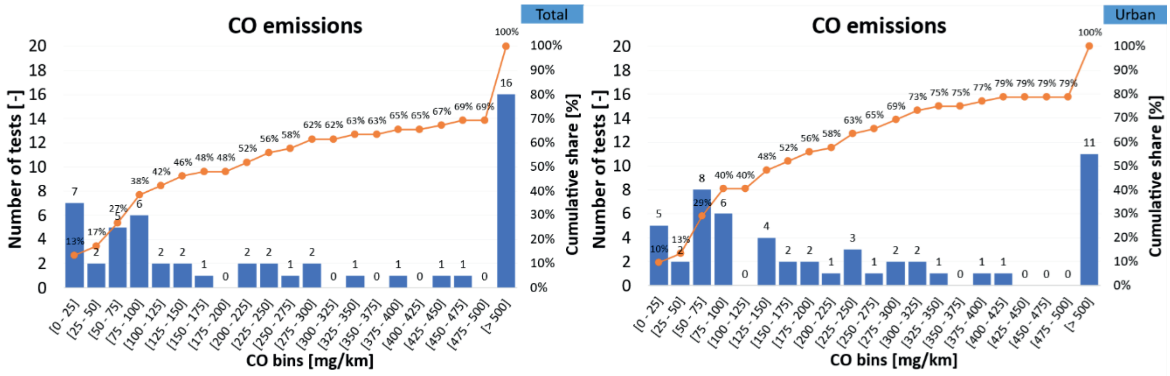


Figure 4-21: CO emissions performance distribution of all tests (beyond RDE boundaries) of Euro 6d vehicles only

4.2.3 Emissions performance on currently non-regulated species

Figure 4-22 presents the NH_3, CH_4, THC, N_2O emission performance of the Euro 6d and 6d-temp vehicles from the CLOVE database. As further discussed below, these pollutants were found to be challenging for the different powertrain types, while the complete analysis and the other components (including non-regulated pollutants) are presented in section 2.1.2 of Annex 2. The test data presented here correspond to laboratory tests, as no equipment was available for on-road measurement of these species. The test cycles evaluated comprised WLTC, TfL, BAB130, US06 as well as RDE on-dyno. Apart from the cycle-average emissions, each test is separated in urban, rural and motorway part following the velocity boundaries prescribed in the RDE regulation (i.e., urban <60 km/h etc.). No separation between Euro 6d and 6d-temp vehicles was performed in this case, as test data are much more limited compared to the RDE tests.

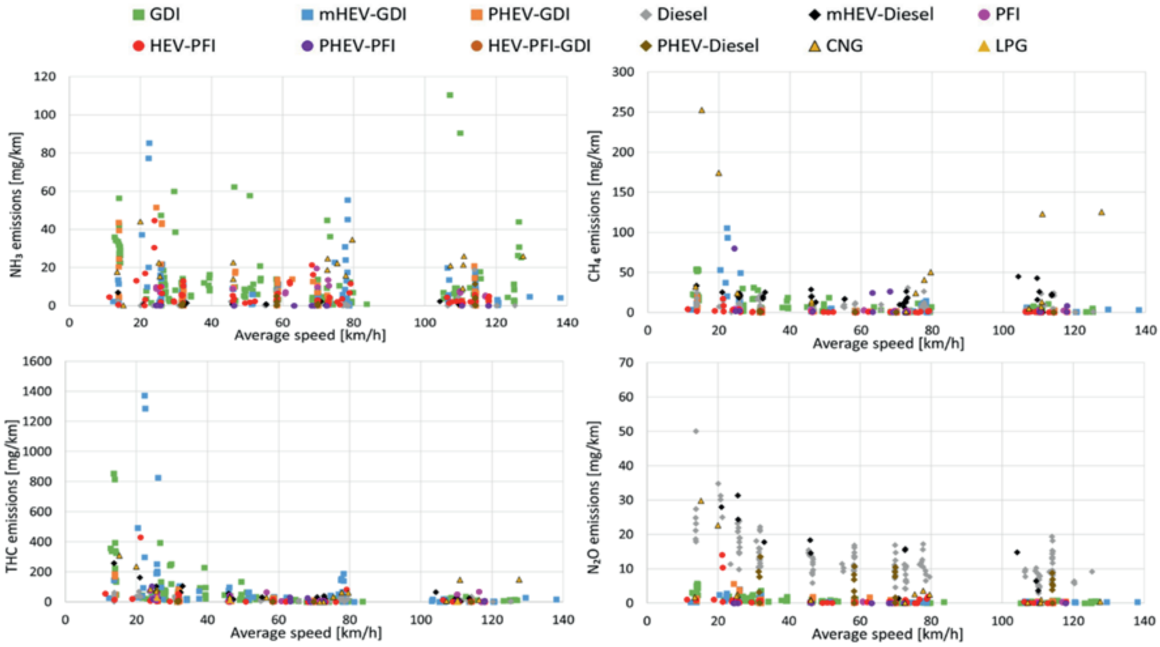


Figure 4-22: NH_3 (top left), CH_4 (top right), THC (bottom left) and N_2O (bottom right) emissions for each powertrain type over laboratory test cycles

High variation is observed among the different powertrain and fuel types. The highest NH_3 emissions are detected in petrol vehicles and mainly in GDI powertrains, while emissions of SCR-equipped vehicles remain at low levels even for those not equipped with ASC. Petrol vehicles were also found to have the highest THC emissions, while CH_4 is high in CNG vehicles. Finally, high N_2O emission levels are clearly dominated by diesel vehicles.

4.2.4 Testing conditions associated with emissions excursion

As presented in the previous sections, emission levels of Euro 6d and 6d-temp vehicles are at low levels especially when tested within the current RDE conditions, i.e., under the test conditions that they were designed for and type-approved. Under such conditions, a significant part of the measured emissions is even below the half of the strictest current limit, highlighting already the potential of current technologies. However, a clear increase of emissions is observed in many vehicles when these are tested under a wider range of driving conditions. This trend is observed in both the regulated and the currently non-regulated emissions species. The deficiencies and the remaining issues observed can be summarised as follows:

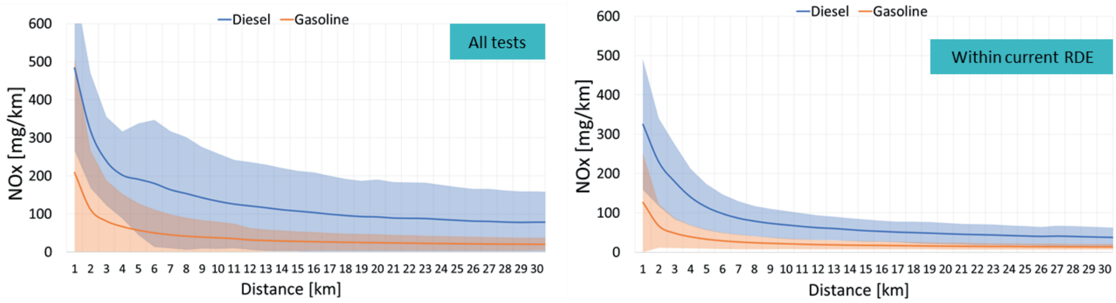
- Cold start – short trips
- Low ambient temperature
- High engine power events/periods:
  - Harsh accelerations
  - Uphill driving, high vehicle payload and/or trailer pulling
  - High vehicle speed
- High PN emissions:
  - During and immediately after DPF regeneration and when filter is clean
  - From technologies currently not included in regulation (PFI and CNG)
- Other high-emission events observed in specific vehicles:

- During idling and low load driving which may occur during traffic congestion (severe stop-and-go situations).
- After engine motoring and fuel cut-off phases

Each of these issues is considered in turn below.

Cold start – short trips

Figure 4-23 presents the evolution of NOx, CO and SPN_{23} emissions (in mg/km and #/km) for all the tests (left part) of the CLOVE database and only the RDE-compliant ones (right part). The graphs present the average emission values in 1-km bins (i.e., 0-1 km, 0-2 km, 0-3 km etc.) for diesel and petrol powertrains (blue and orange lines respectively), while the areas above and below the average line show the standard deviation among the different vehicles. Cold start is found to be one of the main contributors of elevated emissions, especially in short trips, typically below 5-8 km. NOx emissions are significantly higher in the first 3-5 km compared to the rest of the cycle (NOx emissions at 2 km are 3.3 times higher compared to 16km), while a similar trend is observed in CO emissions, mainly in tests within current RDE. When all tests, both within and beyond RDE boundaries, are taken into consideration CO emissions of petrol vehicles are found to be at high levels even after the cold start period. This is an indication of the relatively poor performance and lambda-1 control of current vehicles under high load/power demand operation. This can be attributed to the decision of some OEMs to adjust engine calibration towards NOx suppression instead of CO, as there is currently no CO RDE limit. The cold start effect is also detected in SPN_{23} emissions (log scale), although in this case the loading state, and consequently the filtration efficiency of particulate filters (DPF or GPF) during the test, is also an important parameter. Finally, as a general comment, although these graphs do not intend to illustrate the differences between tests within and beyond the current RDE boundaries, it is obvious that emission performance is different when all tests are included compared to the case where only tests within RDE boundaries are evaluated (as in the case of CO emissions discussed above). What is important in the case of the tests beyond RDE boundaries is the frequency of these conditions in real life and the overall environmental effect. This is a rather challenging and complicated topic, as this frequency may significantly vary among the different vehicle categories, countries, and temperature zones. Additional input and discussion on this topic is provided in Chapter 6, where the recommendations for the test conditions for the next regulation step are presented.



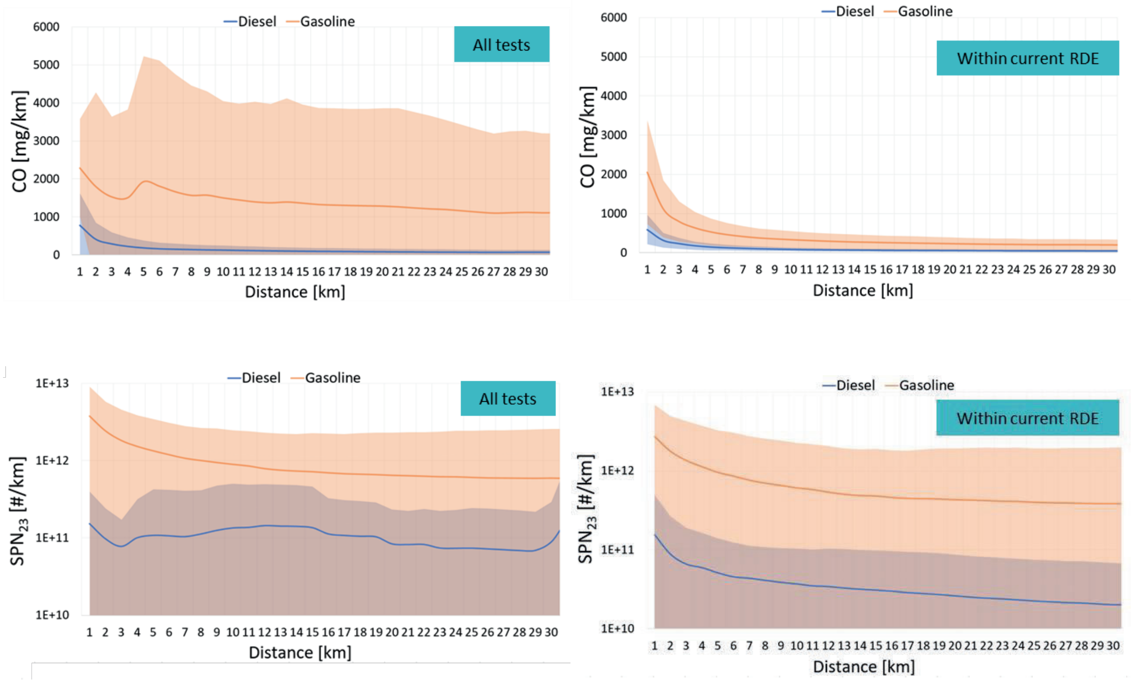
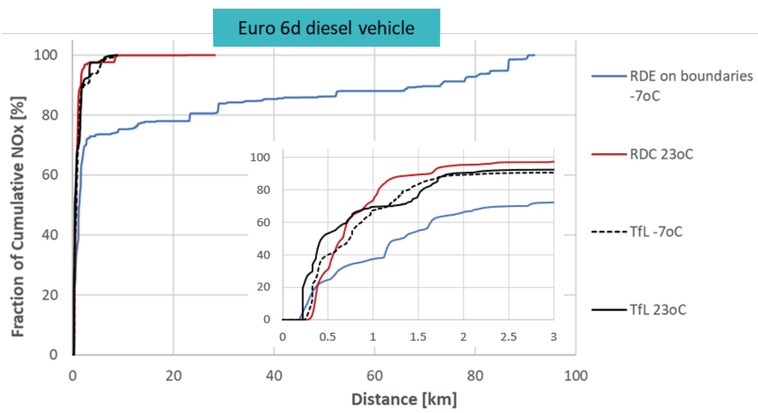


Figure 4-23: Evolution of NOx, CO and SPN_{23} emissions in 1-km bins

Figure 4-24 presents the evolution of cumulative NOx emissions (as a percentage of cycle-total cumulative emissions) under several test cycles for three example vehicles tested by the JRC, a Euro 6d diesel equipped with double urea injection, a Euro 6d-temp GDI vehicle (TWC+GPF) and a Euro 6d GDI PHEV (TWC+GPF). Table 4-1 presents the contribution of cold start period (either the first 5 minutes of engine operation or until coolant temperature reached 70°C following the RDE regulation). Focusing on the conventional diesel and petrol vehicles, it can be observed that the contribution of cold start is higher in shorter cycles (e.g., above 70% in TfL), while lower contributions are observed in longer and more dynamic tests (e.g., worst-case RDE). A comparison between the diesel and the (conventional) petrol vehicle reveals a shorter cold start period in the case of petrol vehicle which reaches a plateau in the first 200m of all test cycles. This can be attributed to the lower time until catalyst light-off in the case of petrol due to higher exhaust gas enthalpy compared to diesel. In the case of the PHEV, cold start contribution is again high in short cycles, but high emission peaks are observed still within the tests, owing to the intermittent operation of the combustion engine as well as to not precise lambda control.



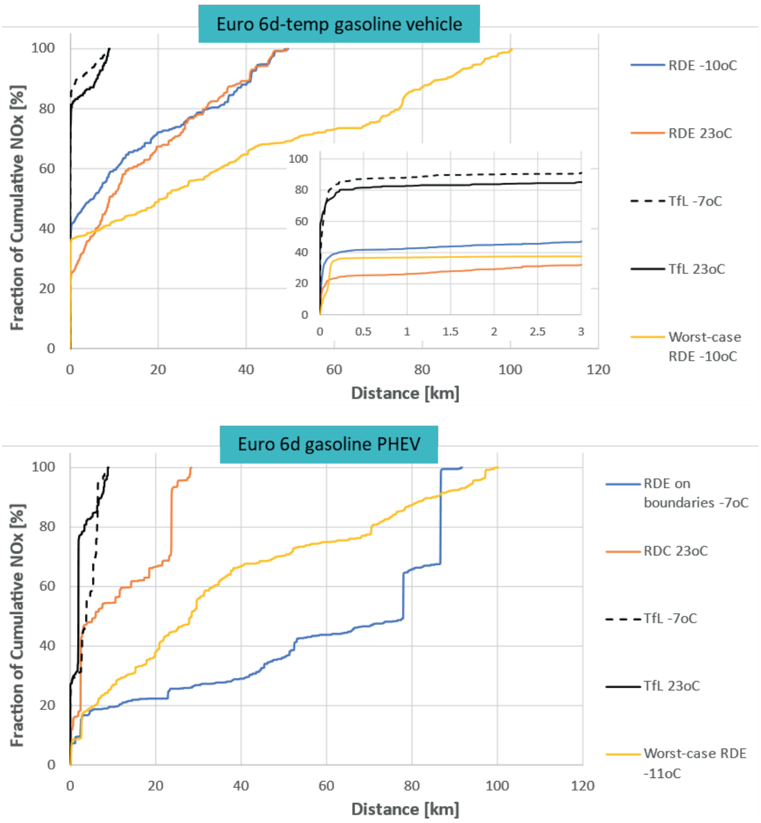


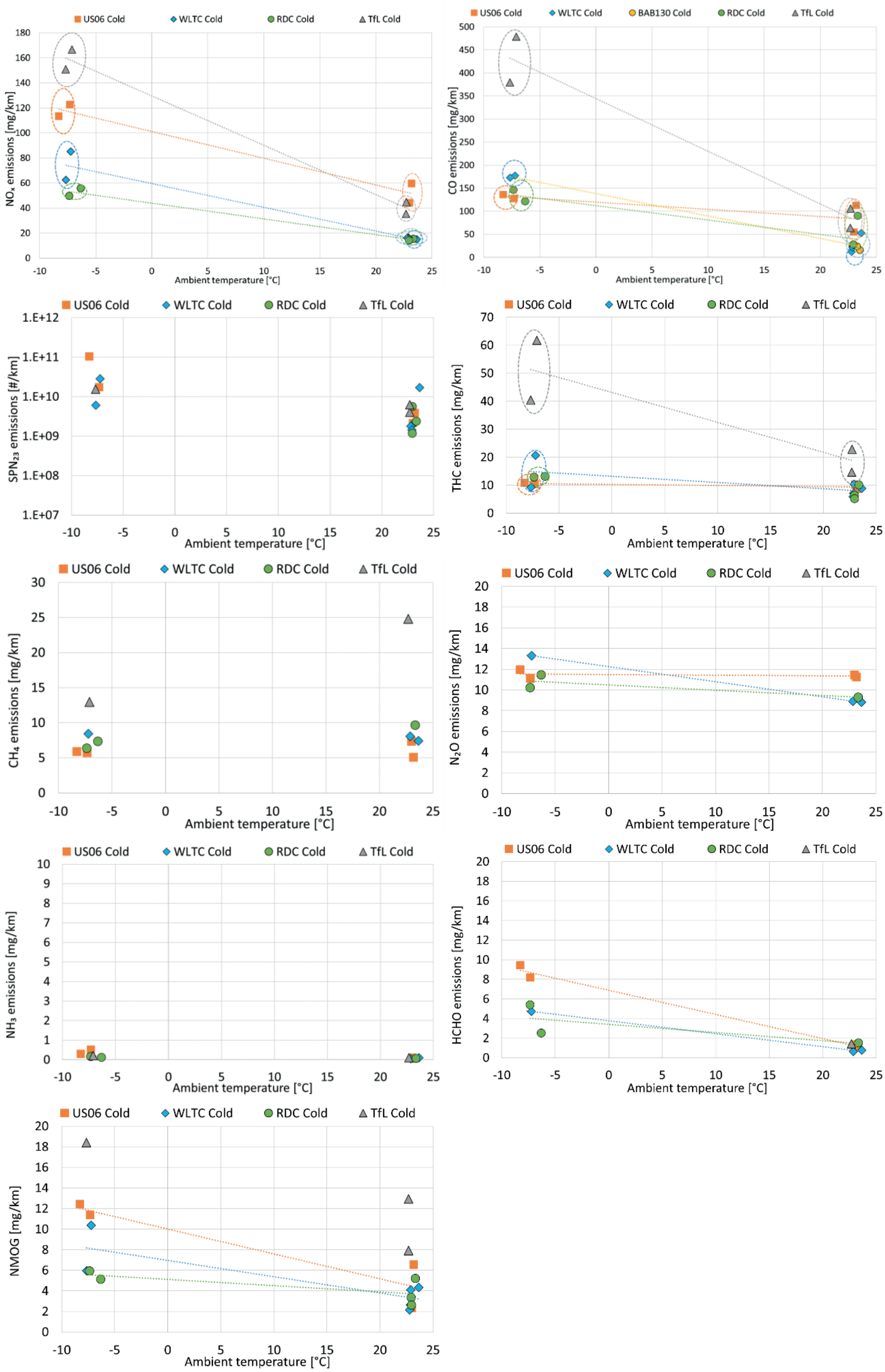
Figure 4-24: Evolution of cumulative NOx emissions for a diesel, a petrol and a PHEV (dyno tests)

Table 4-1: Cold start contribution on cumulative NOx emissions for the different test cycles and tested vehicles

Vehicle	Test	Cold start contribution [%]
Euro 6d diesel	RDE on boundaries -7 ºC	65%
	RDC 23 ºC	93%
	Tfl 23 ºC	72%
	TfL -7 ºC	68%
Euro 6d-temp petrol	RDE -10 ºC	44%
	RDE 23 ºC	29%
	Worst-Case RDE -10ºC	39%
	Tfl 23 ºC	83%
	TfL -7 ºC	88%
Euro 6d petrol PHEV	RDC 23 ºC	45%
	Tfl 23ºC	56%
	RDE on boundaries -7 ºC	12%
	TfL -7 ºC	31%
	Worst-case RDE -11 ºC	16%

Low ambient temperature

Figure 4-25 and Figure 4-26 present the effect of low ambient temperature (cycle-average and cumulative emissions) for a Euro 6d diesel (DOC+sDPF+2xSCR+ASC) and a Euro 6d-temp GDI (TWC+GPF) vehicle. For each vehicle, tests (in a climatic chassis dynamometer) were performed at different ambient temperatures, from ~-7°C to ~+23°C for the diesel and from ~-30°C to ~+50°C for the GDI. Diesel vehicle results show that cycle-average NOx emissions increase by up to 4.7 times at low temperatures (WLTC), while an increase of up to 6.4 times is observed in CO emissions (WLTC). As regards non-regulated emissions, in some pollutants the effect of low ambient temperature is high, while in others (e.g.NH_3 and CH_4) there is no clear trend. In most cases, especially in the GDI (for the complete analysis look at section 2.1.2 of Annex 2), as shown in the lower panel of Figure 4-26, the main difference between low and the high/moderate temperature tests is observed during the very first part of the cycle, indicating that cold start emissions are significantly increased at low ambient temperatures. After the cold start period, emissions are almost identical between the two temperature levels.


US06 Cold
WLTC Cold
RDC Cold
TfL Cold
NOx emissions [mg/km]
Ambient temperature [°C]
US06 Cold
WLTC Cold
BAB130 Cold
RDC Cold
TfL Cold
CO emissions [mg/km]
Ambient temperature [°C]
SPN23 emissions [#/km]
Ambient temperature [°C]
THC emissions [mg/km]
Ambient temperature [°C]
CH4 emissions [mg/km]
Ambient temperature [°C]
N2O emissions [mg/km]
Ambient temperature [°C]
NH3 emissions [mg/km]
Ambient temperature [°C]
HCHO emissions [mg/km]
Ambient temperature [°C]
NMOG [mg/km]
Ambient temperature [°C]

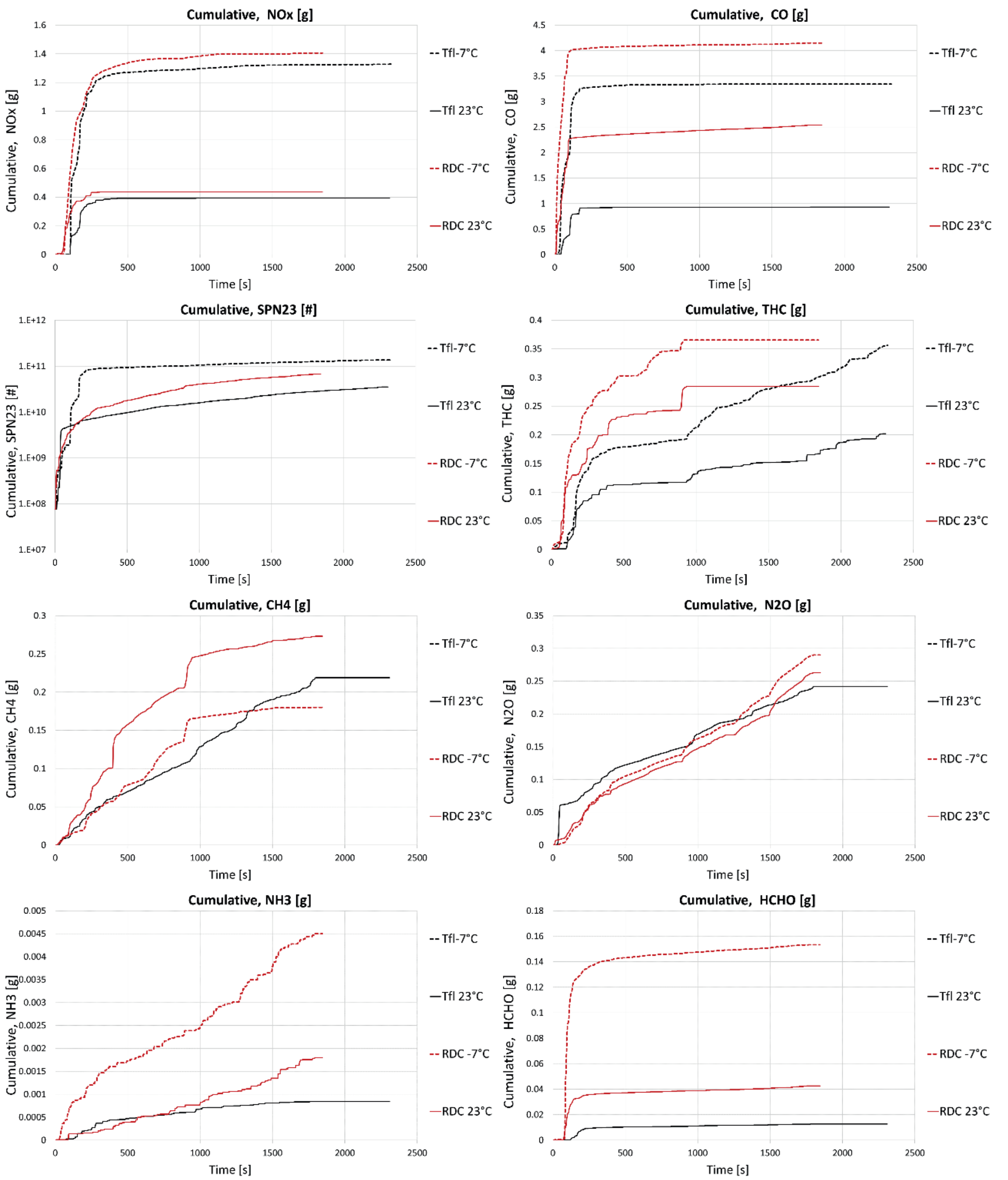
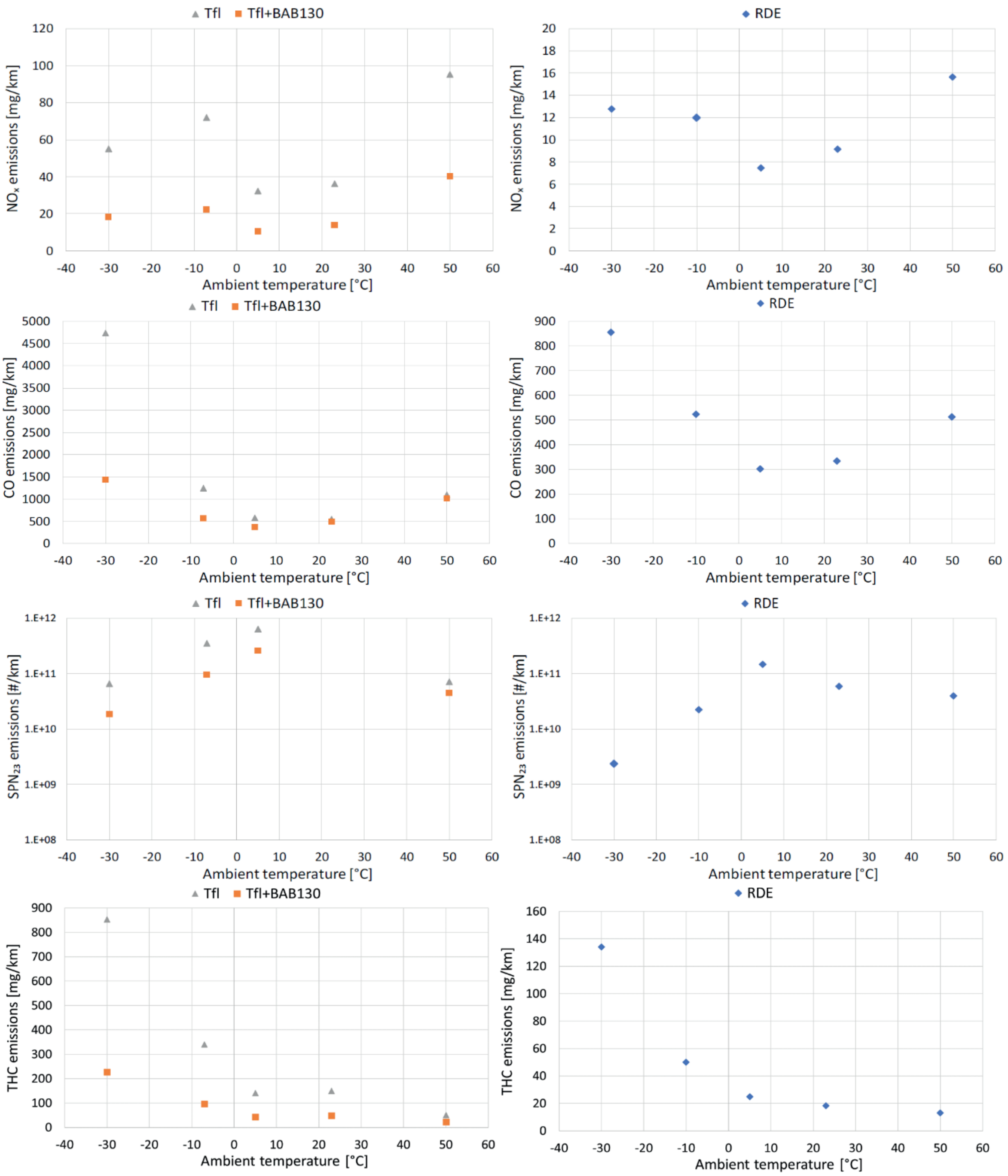
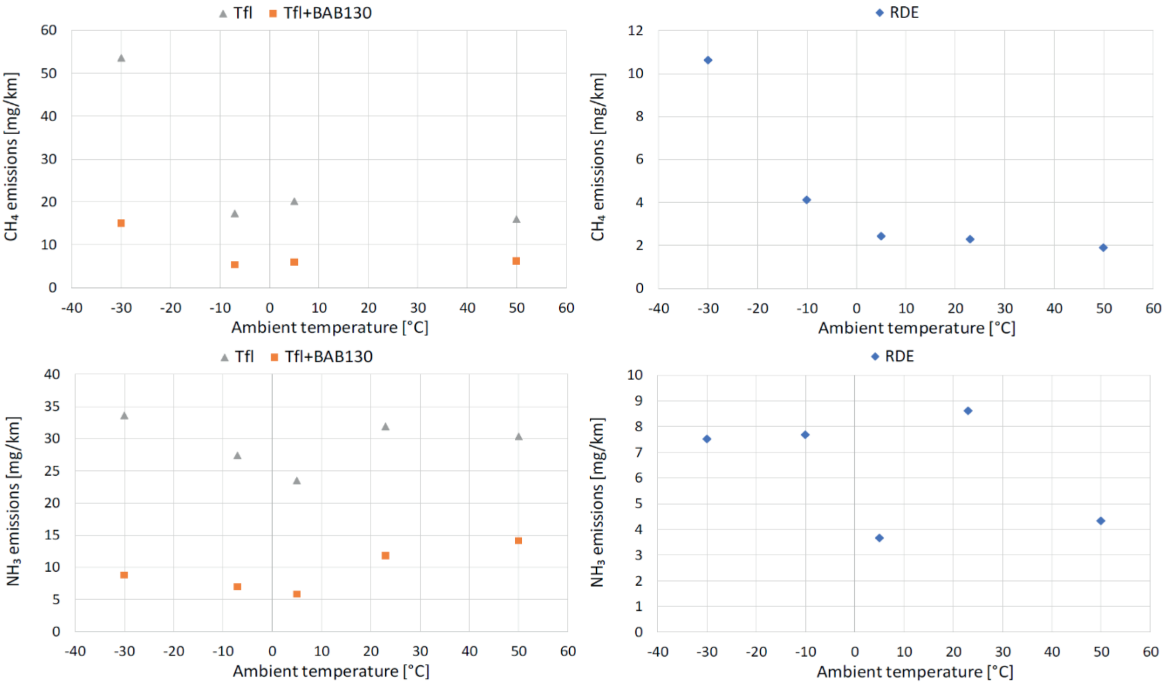
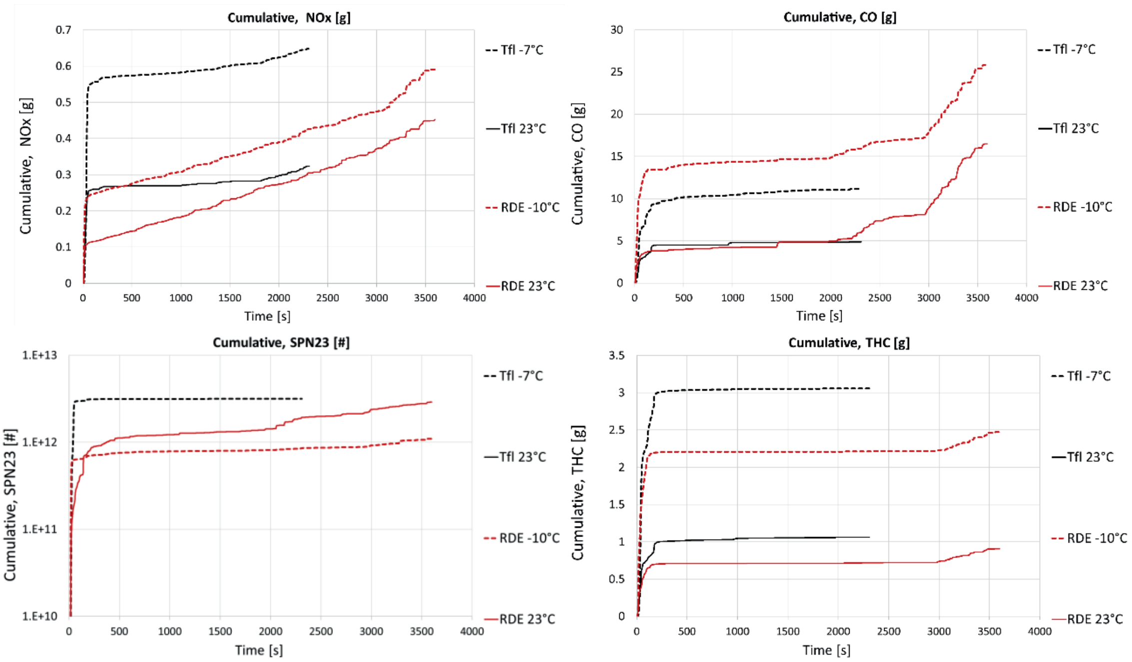


Figure 4-25: Impact of low temperature on emissions (upper group of graphs: cycle-average emissions, lower group of graphs: evolution of cumulative emissions) of a Euro 6d diesel vehicle over various (lab) test cycles.


Tfl
Tfl+BAB130
RDE
NOx emissions [mg/km]
CO emissions [mg/km]
SPN23 emissions [#/km]
THC emissions [mg/km]
Ambient temperature [°C]


Tfl
Tfl+BAB130
CH₄ emissions [mg/km]
Ambient temperature [°C]
RDE
CH₄ emissions [mg/km]
Ambient temperature [°C]
Tfl
Tfl+BAB130
NH₃ emissions [mg/km]
Ambient temperature [°C]
RDE
NH₃ emissions [mg/km]
Ambient temperature [°C]


Cumulative, NOx [g]
Cumulative, NOx [g]
Time [s]
Tfl -7°C
Tfl 23°C
RDE -10°C
RDE 23°C
Cumulative, CO [g]
Cumulative, CO [g]
Time [s]
Tfl -7°C
Tfl 23°C
RDE -10°C
RDE 23°C
Cumulative, SPN23 [#]
Cumulative, SPN23 [#]
Time [s]
Tfl -7°C
Tfl 23°C
RDE -10°C
RDE 23°C
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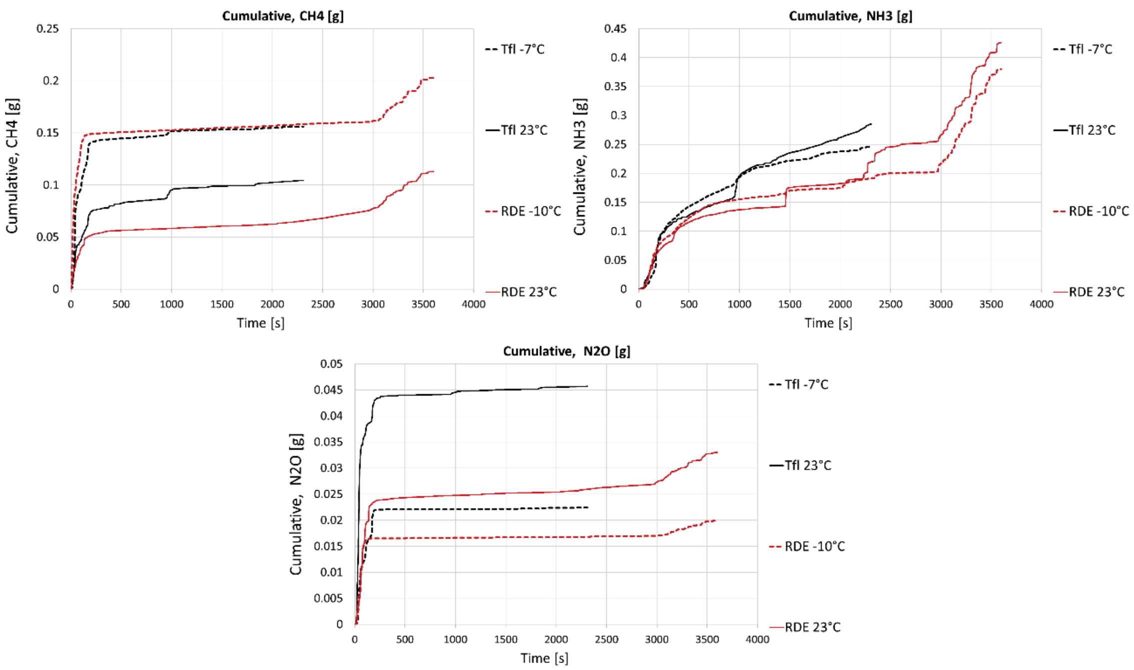


Figure 4-26: Impact low temperature on emissions (upper group of graphs: cycle-average emissions, lower group of graphs: evolution of cumulative emissions) of a Euro 6d-temp GDI vehicle over various (lab) test cycles.

High engine power events/periods

High engine power events include harsh accelerations, uphill driving, driving with high vehicle payload and/or trailer pulling, and high vehicle speed driving phases. Figure 4-27 presents the NOx and CO emissions evolution of a Euro 6d-temp GDI (TWC+GPF) over a wide range of test conditions. These include RDE tests at different ambient temperatures from -30°C to +50°C, a combined test comprising the TfL and BAB130 cycles at the same temperature range as the RDE, two uphill routes at low ambient temperature (down to -10°C) with extra load due to trailer towing (trailer mass up to 1700kg), and a test called “worst-case RDE”. The latter is a combination of different worst-case conditions including low ambient temperature (-10°C), 90% payload (no trailer) and high driving dynamics i.e., several harsh acceleration and decelerations events. This test cycle is further analysed in Chapter 7, as it was used for the (simulation-based) evaluation of EURO 7 technology packages.

A clear increase of emissions, in particular CO, was detected in some vehicles when tested under dynamic driving and during motorway parts. This comes as a result of fuel enrichment, indicating that close lambda-1 control is needed. In addition, a significant increase of emissions is observed in most cases over the BAB130 test which includes harsh accelerations under motorway high-speed driving. The effect of high engine power on emission levels is further illustrated in Figure 4-28, which presents the correlation between the average cycle (positive) power demand normalised to the highest value among the different values, and the corresponding emission levels for NOx and CO emissions. For this analysis only the low-temperature (-7oC to -10oC) tests of the Euro 6d-temp GDI (TWC+GPF) vehicle were selected to avoid any temperature-dependent effects. In both pollutants, an increase of cycle power is related to a proportional increase of emission levels.

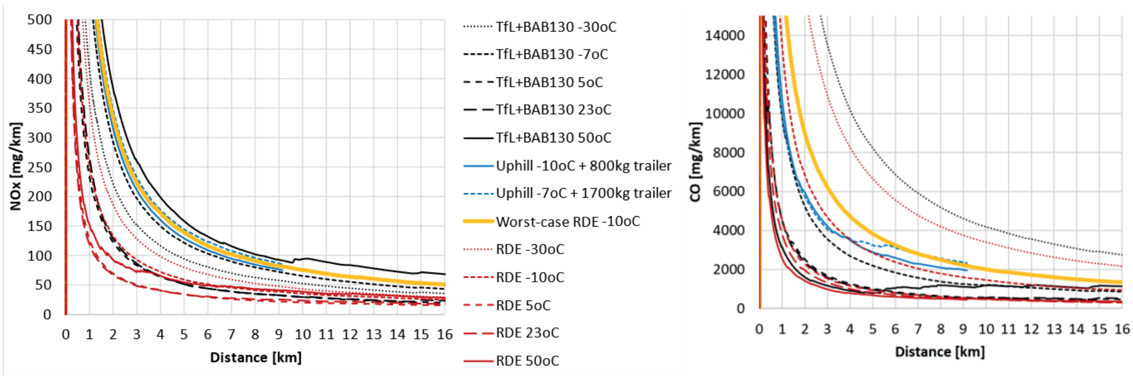


Figure 4-27: Evolution of NOx and CO emissions of a Euro 6d-temp GDI vehicle under several test cycles (chassis dynamometer tests) covering a wide range of test conditions

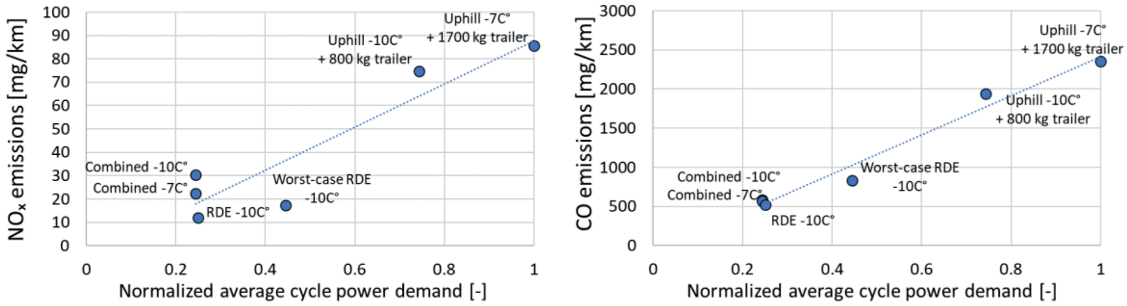
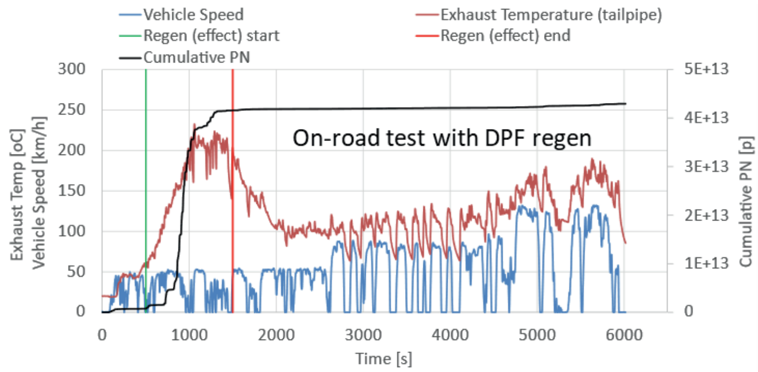


Figure 4-28: Correlation of average power demand and emission performance of a Euro 6d-temp GDI vehicle under several low-temperature test cycles (chassis dynamometer tests)

DPF regeneration

PN emissions of diesel vehicles remain at low levels (1-2 order of magnitudes lower than the Euro 6 limit, 6×10^{11}) under a wide range of driving conditions both within and beyond the current RDE boundaries, as presented in sections 4.2.1 and 4.2.2. However, DPF regeneration was found to cause a significant increase of emissions by more than 2 orders of magnitude. As an example, Figure 4-29 presents the evolution of SPN_{23} emissions and exhaust tailpipe temperature of a Euro 6d-temp diesel vehicle over an RDE test with DPF regeneration (upper panel) and a test over the same route without a DPF regeneration (lower panel). The green and red vertical lines indicate the period that SPN_{23} emissions are affected by the DPF regeneration due to low DPF filtration efficiency. The main criterion for the determination of this period is the evolution of cumulative SPN_{23} emissions, which in this example increases by 55 times during this period. It should be noted that this period does not totally coincide with the actual DPF regeneration period both in terms of start and end, as filtration efficiency at the beginning of regeneration remains high until a sufficient amount of soot is oxidised, while the filter is still empty (thus with low filtration efficiency) for a period after the regeneration end until a sufficient soot cake is formed again.



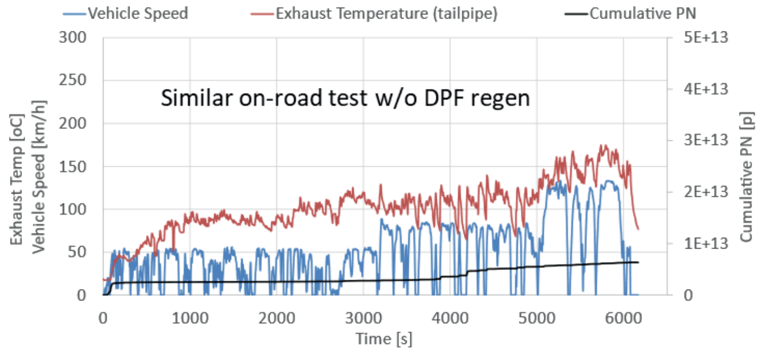


Figure 4-29: Evolution of cumulative SPN emissions over two RDE tests (on the same route) with and without DPF regeneration

Figure 4-30 presents a comparison of SPN_{23} emissions of four vehicles included in the CLOVE database on tests with and without DPF regeneration as well as the emission levels during the DPF regeneration period (this period again refers to the period that PN emissions are affected by the DPF regeneration). Cycle-average emissions of test including a DPF regeneration are close or above the 6×10^{11} p/km limit (without CF) and 4 to 650 times higher compared to the tests without DPF regeneration. Emissions during the DPF regeneration period are up to 16 times higher than the limit (although not applicable in this case). Emissions during (and immediately after) DPF regeneration are not controlled in Euro 6, thus the CLOVE recommendation is that tests with DPF regeneration are considered valid in EURO 7. The recommended evaluation method is further analysed in Chapter 7.

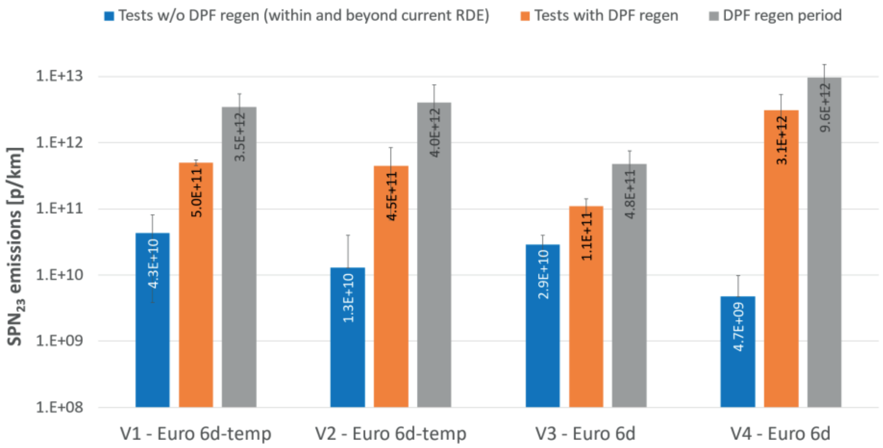


Figure 4-30: Cycle-average SPN_{23} emissions over tests with and without DPF regeneration

Finally, as presented in section 2.1 of Annex 2, DPF regeneration can also result in an increase in gaseous emissions (NOx, CO evaluated for this report). However, our preliminary analysis indicates that in most cases the effect of driving dynamics (in terms of cycle-average emissions) is higher than the effect of DPF regeneration. In addition, CO levels of diesel vehicles remain at much lower levels compared to petrol vehicles even when DPF regeneration is taken into account. This indicates that a weighted approach similar to PN emissions may not be necessary for gaseous emissions too. What should be also underlined is that we foresee that gaseous emissions during DPF regeneration will be better controlled in EURO 7, e.g. with better EGR and SCR/NH_3 injection control/strategy.

Other high-emission events observed in specific vehicles

Figure 4-31 presents the evolution of NOx emissions over two long phases of a cold start on-road test of a Euro 6d-temp diesel vehicle (equipped with LNT+DPF+SCR). The lower panel shows the evolution of exhaust tailpipe temperature revealing that an increase of

NOx emissions occurs at low exhaust temperature in both idling phases (no similar trend was observed in CO emissions). A similar trend was also observed in other diesel vehicles included in CLOVE database, indicating that low load/idling phases can be a challenge in exhaust emission control warm-up and consequently in tailpipe emissions. In this specific test, which was selected as one of the most representative[9], the effect of this idling period on emission can be quantified as follows: the total emitted NOx mass during the two idling periods (~35 minutes) is 1 220 mg. This is similar to the NOx mass emitted by this vehicle over a typical RDE-compliant test (e.g. ~70 km), since the average emissions of this vehicle during RDE compliant tests is 17.4 mg/km. Finally, as a general comment it should be noted that this behaviour was not observed in any petrol vehicle.

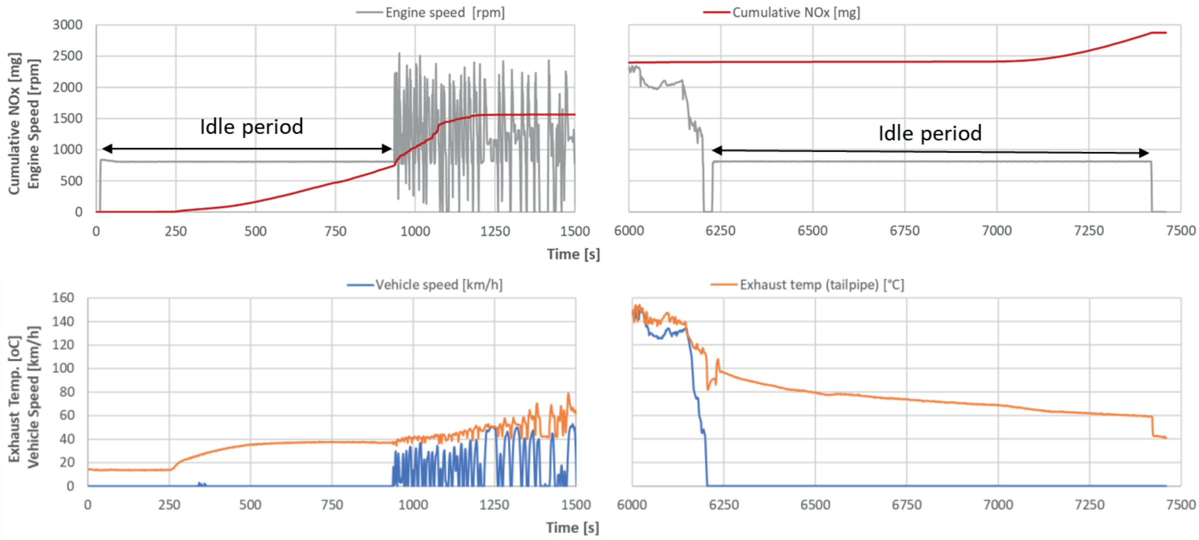


Figure 4-31: Evolution of NOx emissions and exhaust tailpipe temperature over long idling periods of a Euro 6d-temp diesel vehicle

What was observed in the case of petrol vehicles is illustrated in Figure 4-32, which shows the evolution of NOx emissions over a (hot-start) BAB130 cycle of a Euro 6d GDI mild-hybrid vehicle (mHEV) (equipped with TWC+GPF). Vehicle speed, engine torque and CO_2 emissions are provided as additional info. As shown in the graphs, apart from the acceleration phases, NOx emissions peaks are also observed immediately after most deceleration phases (see details in the last graph). This emission increase can be attributed (a more detailed analysis and ideally dedicated testing is needed to further support this analysis and finding) to catalyst overfloating with O_2 during the fuel cut-off period. Thus, when the engine is fired again, the high amount of O_2 stored in the catalyst causes a peak in NOx emissions. A similar trend is observed in other petrol vehicles, especially in cycles with long engine motoring phases.

[9] In some vehicles this issue is less obvious and in others it is not observed at all.

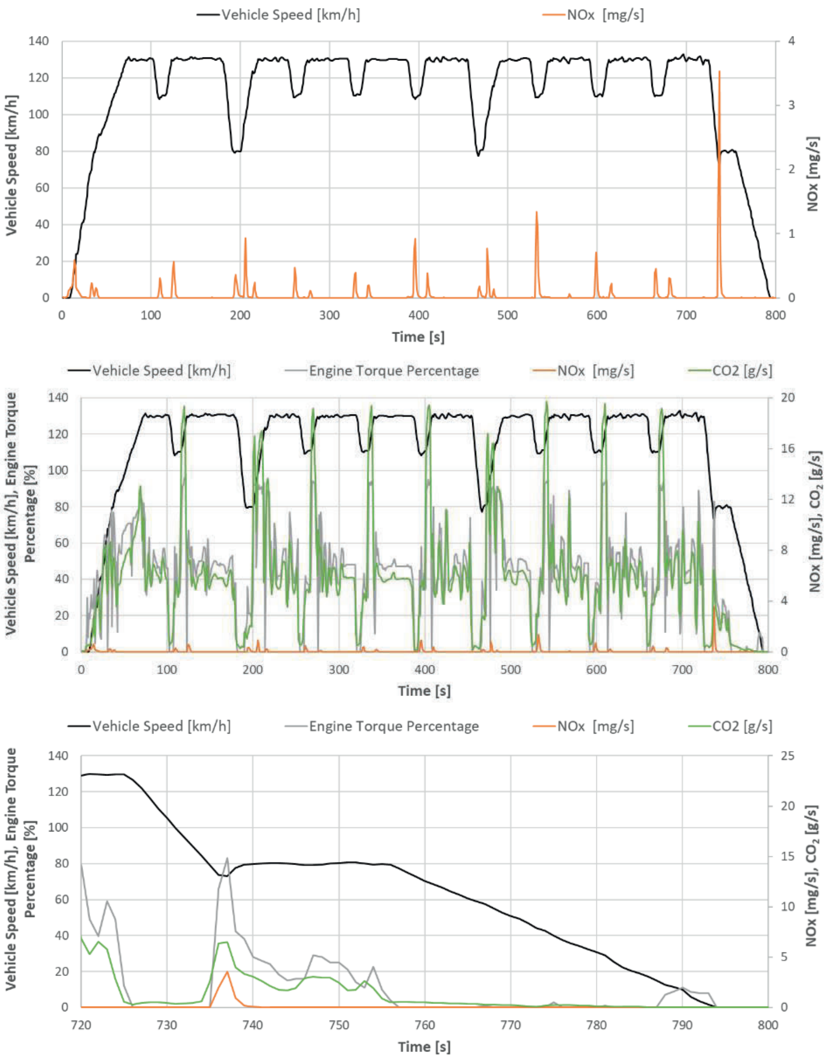


Figure 4-32: Upper and middle panels: NOx and CO_2 emissions, vehicle speed and engine torque over a (hot-start) BAB130 cycle of a Euro 6d GDI mHEV. Lower panel: focus on NOx emission peak after a motoring (fuel cut-off) event.

5 Euro VI emissions performance – HDV

5.1 Evaluation of the technical effectiveness of Euro VI testing requirements

5.1.1 Current regulations

Emissions for heavy duty vehicles under Euro VI standards are tested using World Harmonised Stationary Cycle (WHSC) and the World Harmonised Transient Cycle (WHTC) tests, which are engine dynamometer laboratory-based exhaust emissions tests. The WHTC test applies to both compression ignition (CI) and positive ignition (PI) engines, whereas the WHSC test only applies to CI engines. The introduction of the WHTC and the corresponding cold start test for Euro VI (Regulations (EU) 595/2009 and 582/2011 with their amendments) put the focus in engine development and calibration more towards lower loads and cold start. The additional introduction of on-road emission tests in TA and in ISC brought further reductions of the real-world NO_x emission levels, since an appropriate calibration of the emission control functionalities was needed to meet the limits in the on-road tests.[10] Finally, the obligation to verify CO_2 emissions and fuel consumption of new HDV using the on-road Verification Testing Procedure (VTP) has been in place since 1 July 2020.

The regulations for the on-road emission test procedure with PEMS were further improved for a better coverage of real world driving from Euro VI A (Regulation (EU) 582/2011) to Euro VI E (Regulation 2019/1939). The amendments in Regulation (EU) 2016/1718 extended the allowed engine load for valid tests down to 10% of the rated engine power in the Moving Average Windows (MAW) and a mandatory MAW was introduced with urban-only driving. The current procedure thus better covers low load driving and cold start. In addition, the allowed vehicle payload was extended to be valid between 10% and 100% for the ISC test with PEMS, and cold start emissions are considered.

5.1.2 Assessment of Real-World Performance

Overall, the Euro VI regulations led to reductions in real world NOx emission levels from HDV (Figure 5-1, upper chart) over Euro V and all previous steps. The drop in real-world emissions achieved by Euro VI is visible especially in urban driving, such as for city buses, but also for the average HDV driving. With introduction of a PN emission limit from Euro VI on, PN and PM emission levels were also reduced significantly, thanks to the introduction of particle filters for HD engines (Figure 5-1, lower chart).

From Euro VI E on, PN emissions will also be measured in the on-road tests. This step is expected to bring further reductions in PN emissions since some real-world issues of particle filters have to be improved to pass the ISC tests in all ISC relevant driving conditions.

[10] The parallel introduction of mandatory PEMS tests in type approval and in ISC with EURO VI A/B certainly supported the reduction of the real-world NOx emission levels (the relevance of PEMS and engine testing is discussed later).

Figure 5-1: Average hot NOx (upper) and PN (lower) emission factors for a HDV tractor semi-trailer combination 34–40t and for a city bus (15–18t class) from HBEFA 4.1 for 50 000 km cumulated mileage for their corresponding German traffic situation mix[11]

From Euro VI E on, PN emissions will also be measured in the on-road tests. This step is expected to bring further reductions in PN emissions since some real-world issues of particle filters have to be improved to pass the ISC tests in all ISC relevant driving conditions.

Although the average emission levels of HDVs dropped significantly with Euro VI, several open issues remain. In the following subsections the current situation of Euro VI HDV real world emissions is analysed, based on real world measurements from TUG, TNO and VTT. The analysis is split into:

- Coverage of all relevant driving situations - especially low load operation
- Coverage of cold start emissions
- Coverage of emissions over vehicle lifetime and detection of malfunctions

Coverage of all relevant driving situations

The current evaluation method for PEMS tests is based on Moving Average Windows (MAW) with a length of one WHTC work or CO_2 emissions. In a TNO study (Robin

[11] Figure 5-1 is based on emission tests on hundreds of HDVs in real world cycles for the Handbook Emission Factors (HBEFA 4.1, http://www.hbefa.net). Up to EURO VI these tests were performed mainly on chassis dynamometers, then also with PEMS.

Vermeulen and Gijlswijk, 2019), on-board measurement results of 25 HDVs from Euro VI A to C were analysed over the MAW evaluation method (Figure 5-2).

The analysis shows, that compared to the result of evaluating all MAWs, in this example, the exclusion of cold starts from evaluation has only minor effects. Windows with cold start do not necessarily reach the highest emission levels in a PEMS test for the measured EURO VI technologies (cold starts are discussed below in more detail). Eliminating MAWs below the 10% power threshold reduced the result by some 10%. The main effect on the test result usually comes from the 90th-percentile rule, which eliminates the 10% of MAWs with the highest emission levels. The excluded MAWs mostly correspond to urban areas or to transitions from urban to rural or motorway driving. In general, the combination of the current 10% power threshold and the 90th-percentile together tend to reduce the test result well below the levels of 100th-percentile. The 10% power threshold eliminates a lot of windows with rather high NO_x (not necessarily the highest ones) and the 90th percentile removes with a high probability remaining high emitting MAWs. It must be noted, that the EURO VI E regulation includes the cold start at least from 30°C coolant temperature level and above. We assume that this extension will trigger significant improvements in the thermal management during cold starts of HDVs and thus clearly reduce cold start related NOx emissions. EURO VI E certified HDVs were not available for testing at the time of preparing this study. Furthermore, it is important to note that the 100th percentile does not represent the test average emissions but the value of the highest MAW in the test.

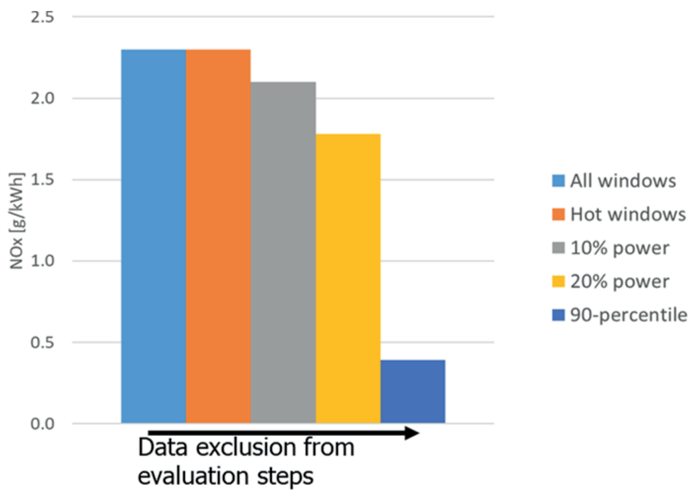


Figure 5-2: Example for the effects from the MAW evaluation method
from Vermeulen and Gijlswijk (2019)

An analysis of various ISC tests performed on EURO VI D HDVs at TUG in a project for UBA Germany (Weller, 2021) shows an average ratio for NOx of 1.3 between the 100th percentile and the 90th percentile of all hot MAWs (Figure 5-3). Exclusion of the 10% of the highest MAWs thus reduces the test result by about 23% on average. The hot MAWs were evaluated starting after one WHTC work was completed to ensure only hot driving conditions are included. This ratio is used also in chapter 8 where a separate limit for hot MAWs is explained.

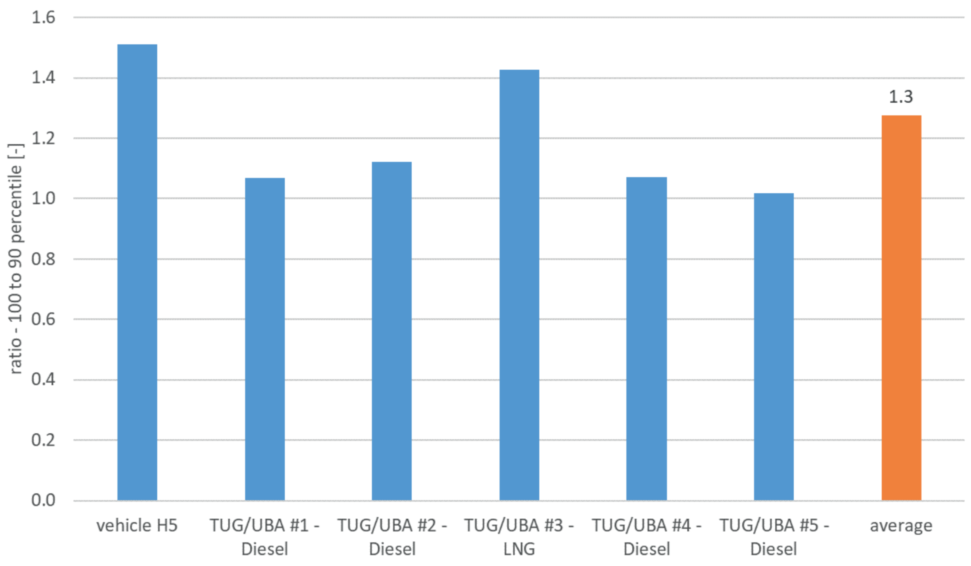


Figure 5-3: Ratio of NOx emissions of the 100th percentile to the 90th percentile of the hot MAWs measured at various ISC tests at TUG in a project for UBA Germany. Test data is described in (Weller, 2021)

During the hot driving phase, high emission events can occur when the SCR first cools down at low loads and then higher power with higher engine-out NO_x is needed from the engine. The duration of such events is typically less than a minute (Figure 5-4), due to fast heat-up of the SCR at higher engine loads. Since the emission levels at such semi-cold situations are still much lower than emissions after cold starts, a EURO 7 regulation could apply separate emission limits for cold and for hot driving conditions, with the limit for hot conditions being lower than the one for cold conditions. This would demand further optimisation of the thermal management also in hot driving conditions to prevent SCR cool-down during driving over a larger operation area.

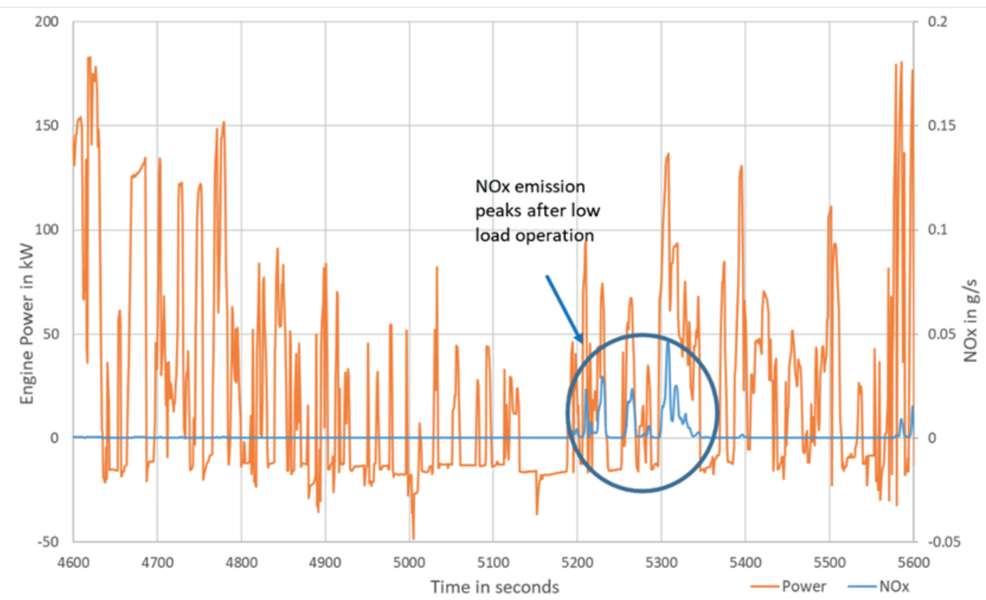


Figure 5-4: Part of power and NOx emission recordings of a PEMS trip from a Euro VI AB HDV distribution rigid truck (measured at TUG)

Low load driving

A main target conflict in HDV NOx control is maintaining low NO_x and high fuel efficiency at low engine loads. The SCR needs sufficient temperature and NH_3 storage levels for high conversion. AdBlue dosing for the NH_3 formation needs exhaust temperatures above approximately 180°C. Below this temperature, the NH_3 stored in the SCR is consumed. This results in a drop of the NO_x conversion efficiency towards zero when no NH_3 is left.

Emission tests performed in real operation over weeks to months of operation in the Netherlands (Vermeulen et al., 2019, 2018a, 2018b), showed a large scatter of average NO_x emissions for various vehicles and operations. The scatter is a result of different driving conditions such as cold starts, trip length, average engine loads etc.). Despite the scattering, this data set shows that at lower speeds, average NOx-emissions are much higher than at high speeds. **The data supports the need to better control low load and cold start driving of HDVs in EURO 7.** It should be mentioned that these emissions shown in Figure 5-5 are not evaluated with the MAW method and thus a comparison with the current ISC limits is not meaningful.

Figure 5-5 shows that at lower speeds, average emissions levels are above the level of the limit value (0.46 g/kWh), even if considering a CF of 1.5 for most of the vehicles. It should be mentioned that these emissions shown in Figure 5-5 are not evaluated with the MAW method and thus a comparison with the current ISC limits is not meaningful.

Low NO_x at low loads is therefore only guaranteed if the test procedures effectively evaluate the emissions under such driving situations. The data shown indicate that cold starts and low load driving could be better covered by future test and evaluation regimes. Allowing shorter test periods than the current ISC (which must achieve 4 times the work done in the WHTC) for on-road tests would support testing also in low load situations within a reasonable time span.

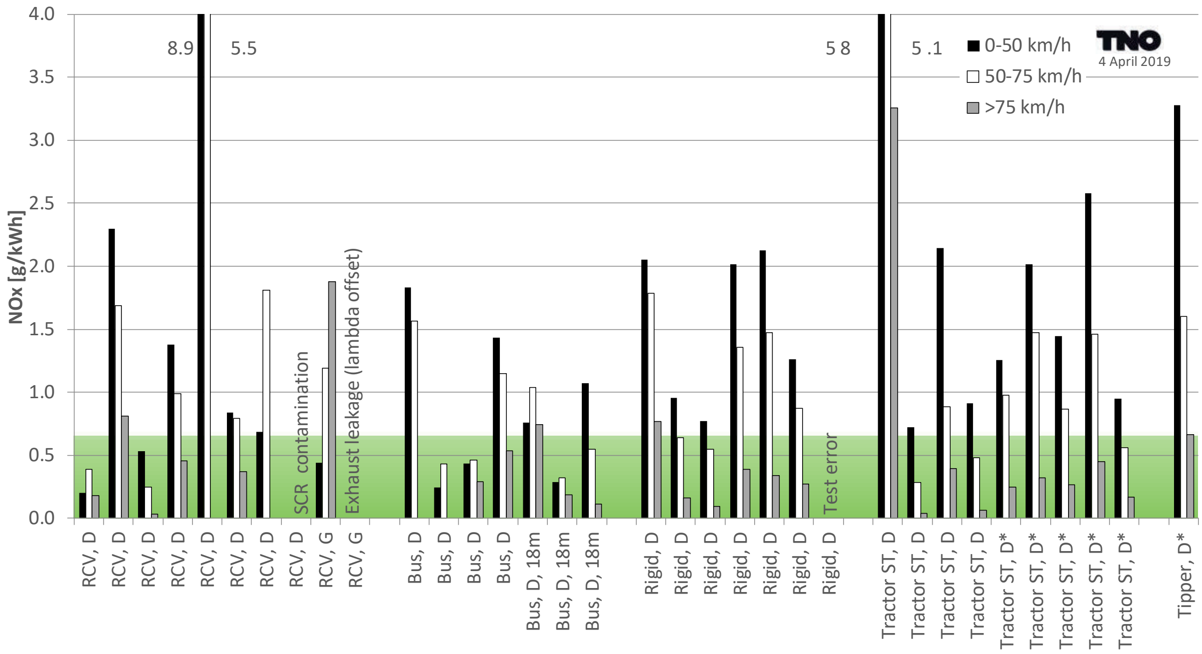


Figure 5-5: Average NOx emissions for 34 different vehicles with Euro VI A or C certified engines in normal daily operations in the Netherlands. (Emissions data are differentiated per speed interval: 0-50, 50-75 and >75km/h)

A special low load event is long idling. Longer idling phases can occur during loading and unloading of vehicles and in hoteling, i.e., when the driver uses the vehicle as a sleeping place overnight and more energy is needed for air conditioning and other consumers than stored in the battery. Figure 5-6 shows test results from a EURO VI D tractor for idling emissions after cold and hot start. The vehicle does not use an external EGR to reduce engine out emissions. Even after hot driving and with air conditioning on, the SCR cools down within circa 10 minutes and NOx increases significantly reaching a level of about 25g/h. With an average engine load of 410W in the test with air conditioning on, the emission level refers to about 60g/kWh. Such long idling phases would not lead to valid MAWs, and thus cannot be compared to the limit values. Moreover, due to the very low load, the g/kWh level is not very meaningful. The hourly emissions can be better compared to emissions during driving, e.g., to the average emissions of the hot ISC test phase of this vehicle which were 10.7 g/h NOx (72.3 kW average power demand with 149 mg/kWh NOx[12]. For CO a significant increase was also found in long idling, while PN emissions remained stable at low levels.

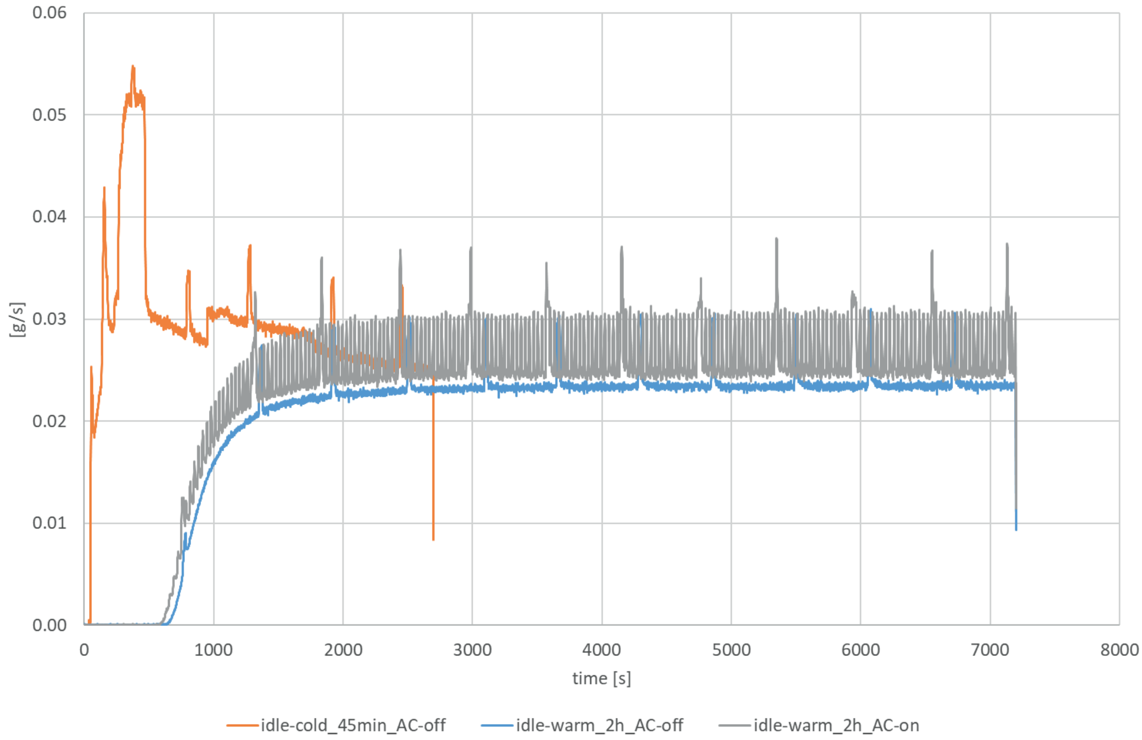


Figure 5-6: Idling emissions from a EURO VI D tractor measured after cold start (orange) and after hot driving (data from measurements for UBA Germany see Weller, 2021)

Coverage of cold start emissions

When efficient catalysts are applied to reduce tailpipe emissions, the emissions between engine start and the time the catalyst has reached the operating temperature contributes over-proportionally to total emissions. This has been an issue for petrol engines with TWC since Euro 1. For diesel engines the introduction of SCR systems leads to a similar situation, since the emissions are very low in hot operation for well controlled systems. As an example, the warm-up time of two EURO VI D city buses tested by CLOVE, at cold and normal ambient temperatures was approximately 25 minutes (10 km) before coolant temperature increased from 0-10°C up to 70°C. When starting the test with warm engines (coolant appr. 60 °C) at cold ambient temperature, warm-up time was still significant at 12

[12] Data evaluated here from vehicle tests commissioned by UBA Germany (Weller, 2021)

minutes (Figure 5-7). Hence, warm-up time typically varies depending on ambient temperature, engine size and design.

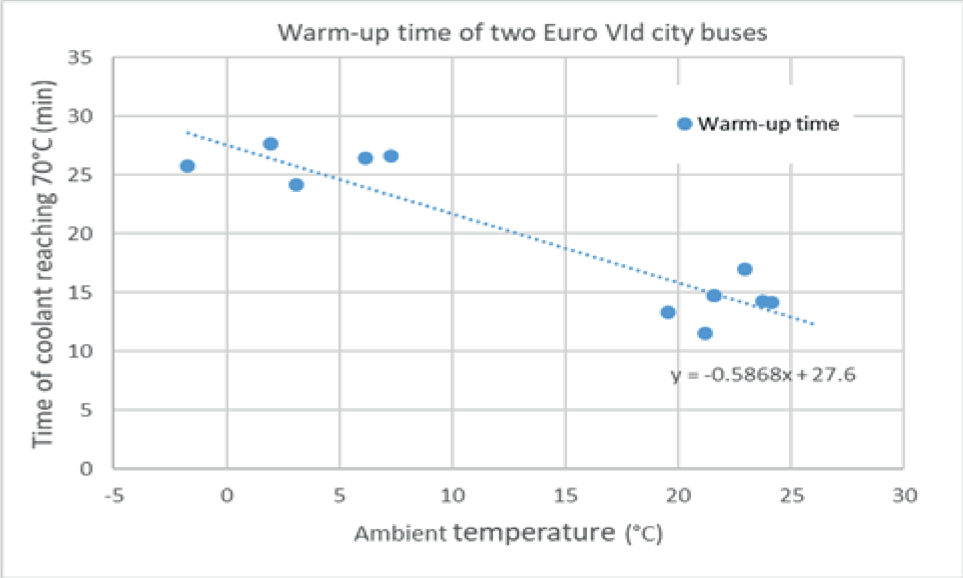


Figure 5-7: Correlation between warm-up times and ambient temperature for two Euro VI D city buses (CLOVE testing campaign)

Hausberger and Weller (2018), evaluated PEMS tests from more than 100 Euro VI HDV for cold start NO_x emissions. For the analysis the extra emissions from engine start until hot driving conditions were calculated as "cold start extra emissions", defined as emissions after cold start minus the emissions with hot start in the same cycle (Figure 5-8). The hot emissions were simulated for this exercise, since only cold started tests were available.

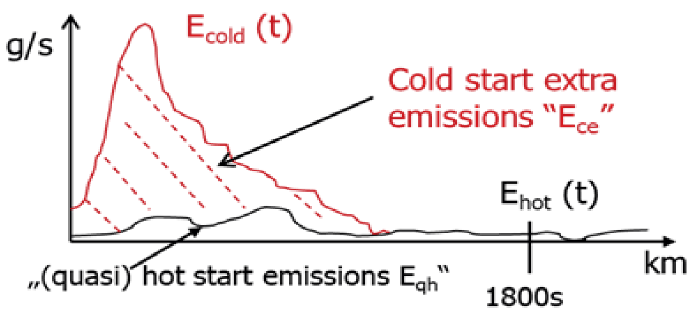


Figure 5-8: Schematic of the cold start extra emissions (Hausberger and Weller, 2018)

Figure 5-9 shows the results for the extra emissions from cold start per PEMS test. A loose correlation to the rated engine power of the tested vehicle was found; no correlation with ambient temperature was identified. This indicates mainly that the influence of the engine design and emission controls on the cold start emission level is much higher than the influence of vehicle weight, engine power and temperature.

Assuming approximately 500 mg/kWh[13] NO_x in hot engine conditions for a well-functioning EURO VI truck in urban driving and approximately 1kWh/km engine work in such a trip, one cold start adds NO_x emissions approximately equivalent to 100 km of hot driving (i.e., ~ 50g). From Figure 5-9 it is also visible that the spread in the cold start extra emissions is quite large, although the test data only covers EURO VI up to step C.

[13] This value represents average trip emissions and includes also low load driving. Thus it is not comparable to EURO VI limit values. For comparison, average Emissions of EURO VI rigid trucks in HBEFA 4.1 are ca. 800mg/kWh in average urban driving

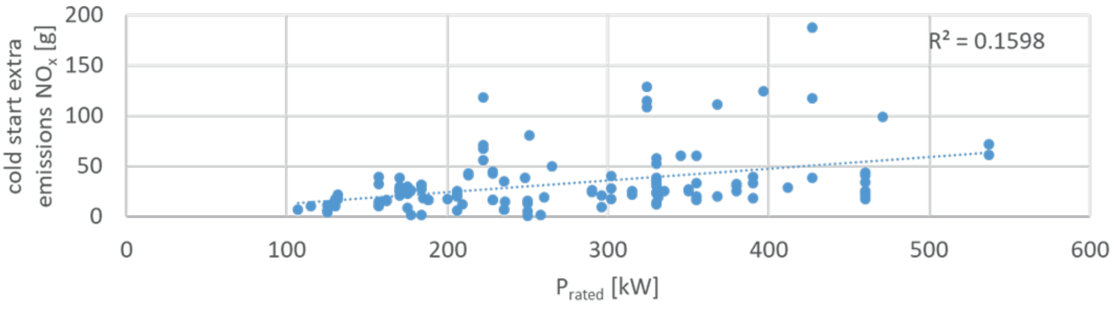


Figure 5-9: NO_x cold start extra emissions from the EURO VI A/B/C HDVs analysed in (Hausberger and Weller, 2018)

A detailed analysis of the HDVs tested within CLOVE and the additional test data collected during the project is provided in the Annex. The analysis shown in the supporting materials is the basis for the emission limit scenarios recommended for EURO 7 HDVs (Chapter 8).

Coverage of emissions over vehicle lifetime and detection of malfunctions

Real lifetime of the HDVs is reported to be clearly longer than the useful life defined in Regulation (EU) 595/2009. As example, Verbeek et al., (2018) reported the following typical lifetime mileages, for different engine size classes:

- 4 to 5 litre: 650 000 km
- 7 to 9 litre: 850 000 km
- 11 to 13 litre: 1 200 000 to 1 800 000 km

The analysis of all HDVs which signed off the registration from 2017 to 2018 in Austria is shown in Figure 5-10. If these vehicles were sold to 3rd countries or scrapped is not recorded. The 90th-percentile of odometer readings from vehicles signed off registration 2017 in Austria are:

- N2: 536 000 km
- N3: 884 000 km

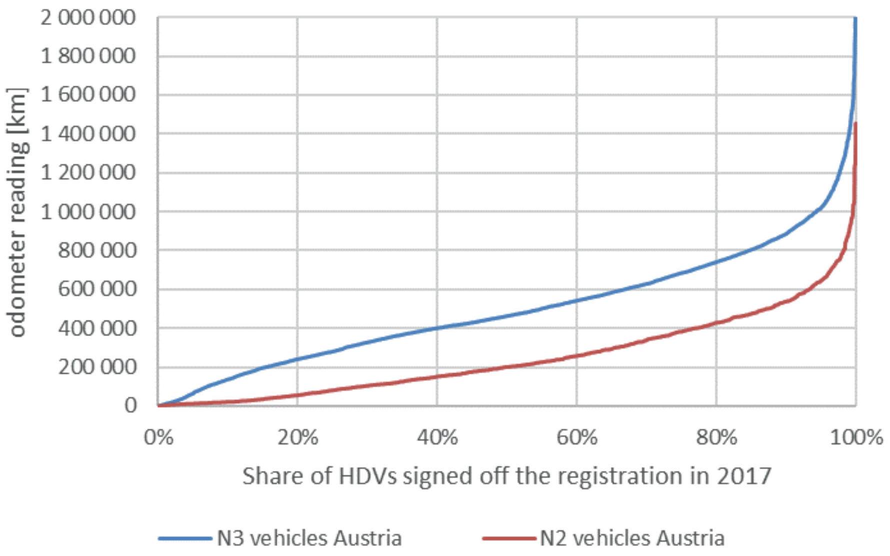


Figure 5-10: Share of HDVs de-registered in 2017 and their mileage

In countries with lower GDP than Austria, it is expected that the actual lifetime of trucks is much larger than indicated by the data presented above. For example, in Greece, the market of trucks and tractors over 3,5t is ten times higher than that of new ones. Even for buses, the market of second-hand vehicles is four times higher than that of new ones. From a search in a popular Greek website (car.gr on April 2, 2020), 21% of the second-hand trucks over 7.5 t have a mileage from 500 000-1 000 000 km and 3% have an even higher mileage. Most of the second-hand vehicles in Greece originate from Germany and Austria.

In a recent report by ACEA (2019), the average age for medium and heavy commercial vehicles in the EU is stated as 12.4 years, varying from 7.2 years to 20.9 years among the EU MS. The lifetime of long-haul trucks and tractors with high yearly mileages is usually lower than for other HDVs.

Emission data are available only for a limited number of HDVs with high mileage. Four older HDVs were tested for the HBEFA 4.1 and until now two vehicles for the HBEFA 4.2 (Figure 5-11). The small sample shows, in some instances, higher NOx emissions from those with higher mileages. On average the tractor trailer data in Figure 5-11 indicate an increase of the NOx level by a factor of approximately 2.5 from low mileage to 800 000 km and even higher for rigid trucks. None of the vehicles indicated malfunctions by activated MIL. However, if some vehicles had malfunctions which were not detected by the OBD or if there were aging effects of the catalysts, the NOx sensors or other emission control devices did not identify the increased emission levels at these tests (Matzer et al., 2019).

In the Netherlands, within in-service testing programme for HDV, various examples of malfunctions were found with substantial increase of NOx emissions:

- EGR valve not working.
- White deposits before, in and after the SCR system leading to high NO_x and NH_3 emissions.
- A defective ambient temperature sensor due to which dosage of reagent stopped entirely during normal operation.

In all cases the MIL was not lit and in the last two cases no emission related error codes were found in the OBD.

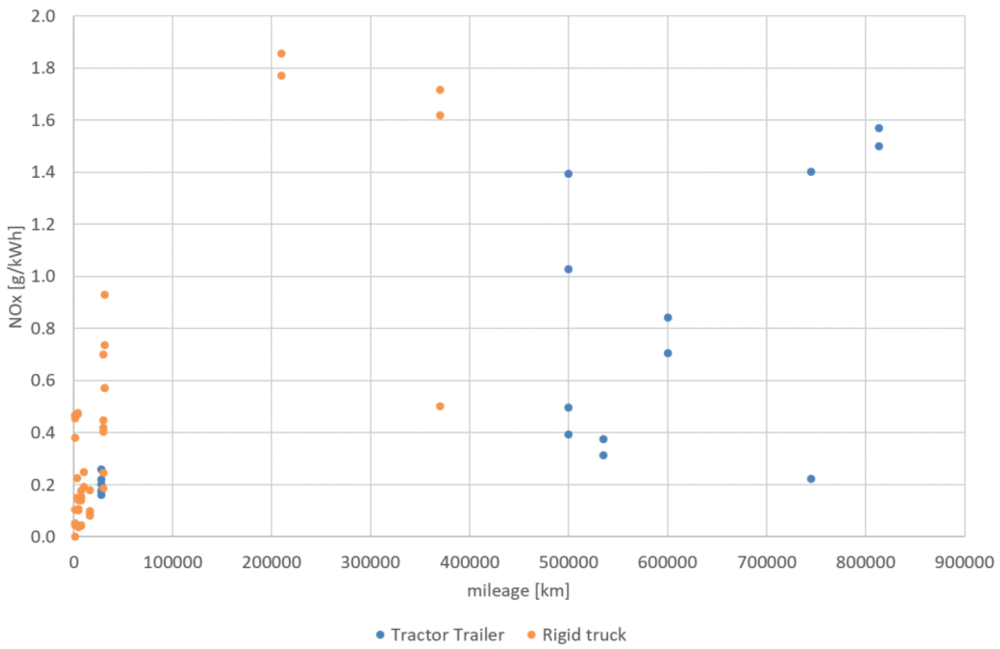


Figure 5-11: NOx emissions from PEMS tests at low and high mileage (data from tests at TUG for HBEFA 4.1 and 4.2)

It is not known if the high emitting vehicles have NOx levels above the OBD threshold of 1500 mg NOx/kWh over the WHTC, since a validation of the emissions in the WHTC in a retest on the engine dyno is very difficult and costly.

5.2 Findings

The main conclusions from the data analysis for EURO VI are:

- Further emission reductions in low load driving and after cold starts could be achieved if EURO 7 included the full cold start and all load conditions as valid vehicle emission tests. This conclusion is supported also by the fact that EURO VI HDVs are not using additional close-coupled aftertreatment systems, which would reduce emissions during cold start and at low loads (see also chapter 8).
- Emissions in hot driving conditions show high variability between makes and models. The hot emissions of the HDV fleet could on average also be reduced in EURO 7 if separate limits for hot driving are introduced (in addition to higher limits including the cold start).
- Long idle periods should also be covered in EURO 7 since an hour of idling can produce more than two times the NOx and CO emissions than an hour of driving.
- The durability of the emissions should be tested in EURO 7 through on-board testing, since a re-testing of the engine on an engine dynamometer needs very high effort and does not safeguard that malfunctions are detected in real world operation. The useful life should be extended and all OBD functions should be active as long as the vehicle is operated in the EU.

6 Testing conditions for EURO 7

6.1 Common elements for light- and heavy-duty vehicles

Since the introduction of on-road testing (RDE and HD PEMS), real-world emissions have considerably decreased in many cases of normal use, with the new vehicles entering the market. For heavy-duty possible limitations in the test procedure remain with most evident the high NOx emissions in urban conditions and low-load engine operation. Such conditions are not well represented in the ISC test evaluation, especially for some vehicle types such as special use vehicles, buses, etc.

Testing conditions for EURO 7 are intended to further increase the coverage of all normal usages of vehicles. The low emission levels observed both for light-duty Euro 6d and heavy-duty vehicles Euro VI Step D should be extended to resolve the few outstanding issues with the robustness of the emission control systems. Both for light-duty and heavy-duty the remaining issues seem linked to the current test requirements, which are discussed below, and this forms the basis of the recommendations for testing conditions for EURO 7.

Heavy-duty vehicles in urban operation such as semi-trailer tractors, refuse collection vehicles, and construction vehicles, are running considerable proportions of urban operating time at low speeds (Figure 6-1). High shares of idling, in some cases for prolonged times, and stops and restarts are normal operation, as can be seen for various cases that were examined in the Netherlands (see TNO reports 2016, 2019 and 2021). The database contains data of normal daily operation of weeks to months of data for representative vehicle types that are operated by Dutch companies mainly in the Netherlands, some also abroad.

Refuse collection vehicles have the lowest average speeds, from 6 to about 26 km/h and have a driving pattern characterised by a high frequency of stops and high share of time where vehicle speed is 0 km/h (35 to 56%) and high shares of driving at low speed (80 to 100% for the speed range of 0 to 50 km/h). Stop times and frequencies depend on the type of refuse collected (small containers, large containers, garbage bags, coarse refuse) and driving speeds depend on the area that is serviced. In cities, speeds are lower as opposed to rural areas and small villages. The lowest speeds and highest idling times were measured in a case of coarse refuse collection with long stops for manual loading of the refuse and short driving intervals.

Average speeds of rigid trucks also show a wide range but are generally higher than for refuse collection vehicles. Rigid trucks include the lighter versions around 10t that are used for city distribution (delivery of goods and parcels) and which typically show the lowest average speeds. Some of the trucks service mainly urban regions and have low average speeds and low shares of motorway driving. Some of the trucks distribute regionally or through the country and drive more on the motorway to enter a city and deliver goods throughout a city which reduces average speeds.

A 4x10 tipper hauls sand to construction sites. It drives from a depot to the site where work consists of a lot of idling standing by, low speed sand dumping and manoeuvring at the site. Hence, the vehicle has a relatively low average speed of 25 km/h and 43% of the time the vehicle is stationary and yet the engine is running. The operation has periods of high engine load when the vehicle is fully loaded with sand versus low engine loads for running empty. Another construction vehicle, a 6x6 container side loader with a PTO powered crane shows similar driving characteristics.

The fraction of idling of refuse trucks, tippers, and trucks in urban distribution are 15% to 50%, compared to 10% and less for long haulage applications. In many cases this idling occurs in urban areas.

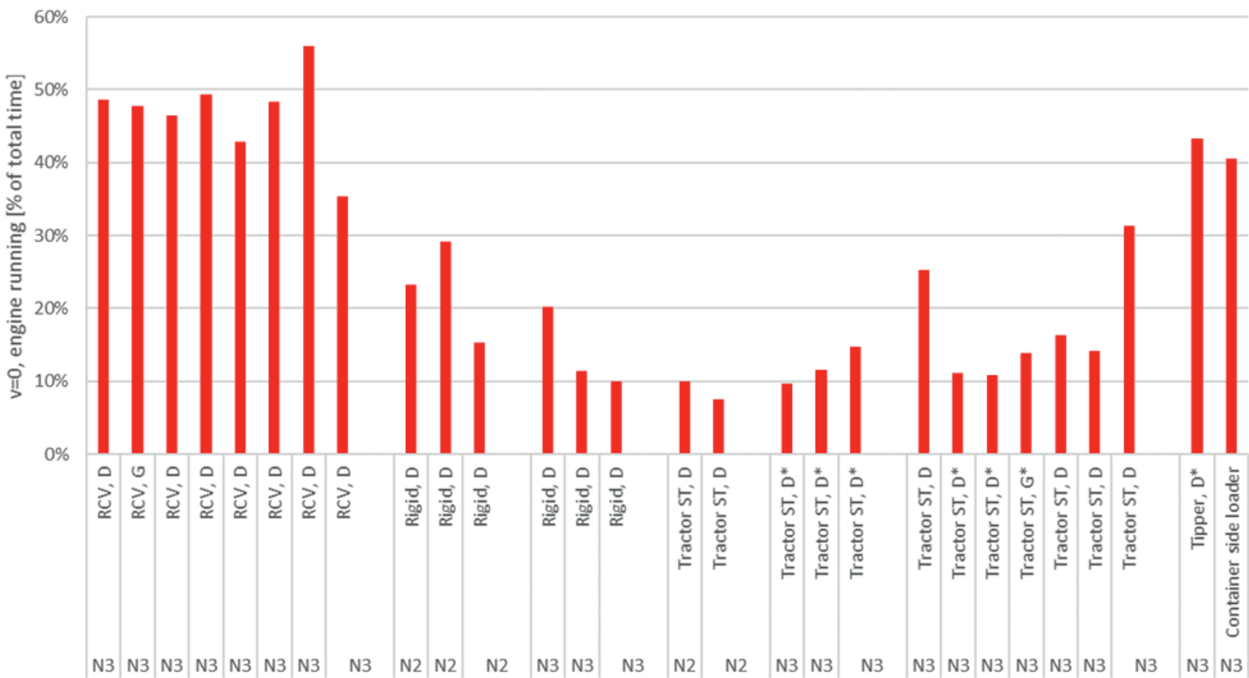


Figure 6-1: Fraction of the total time the vehicle is stationary with the engine on in normal use, for RCV (Refuse Collection Vehicles), rigid trucks, tractors-semi-trailers, a tipper, and a container side loader

For heavy-duty vehicles such monitoring data is very relevant as ISC test data are not representative of normal use in several cases, particularly for urban use. Often, ISC tests are not performed with low payload, as the risk of an invalid test is large. This is related among others to the work window approach, where low load application, for example, an empty return trip is associated with limited work, but even for the latest generation Euro-VI trucks, has substantial NOx emissions. PEMS tests performed on a single 6x6 construction vehicle have shown that it can be difficult to drive a valid trip. Trips needed to be adjusted to meet all the requirements. Trips with normal operation are rendered invalid and changes need to be made to drive a valid trip, such as driving faster in the urban trip part to achieve more than 10% average power. A Euro VI ISC test therefore only represents a small window of normal driving and does not cover other possible normal driving.

Examples are also known for other vehicle types where driving needs to be adapted to meet the requirements, such as vehicles with a high engine power driving with a low payload. In this case, it is hard to achieve MAW with an average power higher than 10% in urban driving. To solve this, the vehicle must accelerate sharply, drive fast, and brake hard to keep the power above the threshold. Low work normal operations lead to two problems in current HD testing: First, in certain operations the 10% power is not met. Second, very lengthy testing, typically several hours, is needed to achieve the required total work. To accumulate the same work as a single WHTC test can require up to two hours in certain types of normal heavy-duty operation.

When new procedures are to be designed for testing real driving emissions of HDV, it should be ensured that trips with normal driving are not rendered invalid and that requirements do not lead to the necessity to make artificial changes to the trip to drive a valid trip. Also, data of normal driving should not be deleted.

For light-duty vehicles, the distant ends of low-power and high-power demand or very low and high ambient temperature are also rather under-represented in the scope of the current RDE testing. For example, as further analysed in section 4.2.4, longer periods of idling (as illustrated in Figure 4-31) and hard accelerations (as shown in the evaluation presented in Figure 4-27 and Figure 4-28) may lead to disproportional increases in emissions for some RDE compliant vehicles (slopes of Figure 6-2), although RDE tests on the same vehicles lead to low emission results, well below the limit (plateau in Figure 6-2). A similar trend i.e., increase of emissions at the left and right ends of Figure 6-2 can be observed in the case of ambient temperature, as illustrated in Figure 4-26. Finally, the effect of short trips (left slope of Figure 6-2) and consequently the high cold start effect on emissions can be further exemplified with the analysis presented in Figure 4-23.

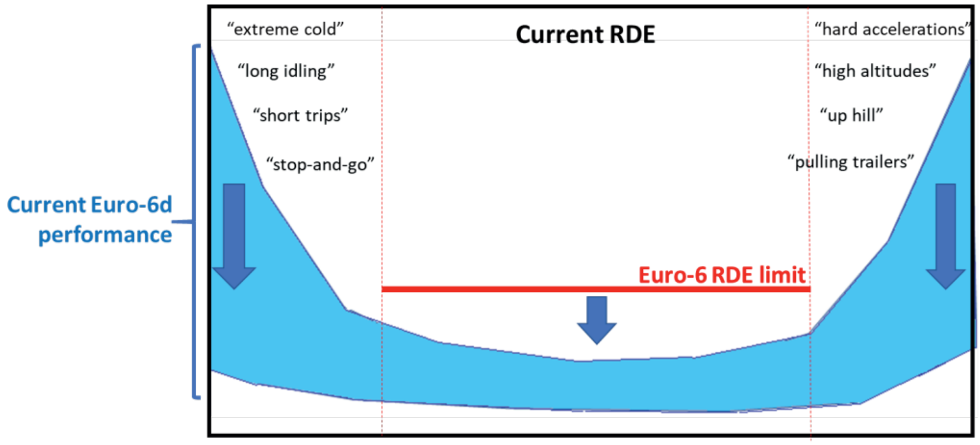


Figure 6-2: "Bath-tub" schematic of emissions performance against current RDE

Central to the question of setting an emission limit is the test procedure this is verified upon. Testing including extreme operation conditions should be followed by a higher emission limit. The current expressions of emission limits in mg/km for light-duty vehicles and g/kWh for heavy-duty vehicles would require an infinite emission limit for tests where the heavy-duty vehicle is only idling, because no distance is driven, and no useful work is done by the engine.

The good emission performance under normal or moderate conditions should be extended to include as wide an area as possible for the normal use of both LDV and HDV operation (see chapters 4 and 5 on performance of Euro 6d and VI-D vehicles). This is in order to offer environmental protection for the majority of operation conditions. On the other hand, any extension of the test domain to include as wide a range of driving conditions as possible should be done with great care, to avoid a very high emission limit associated with an extreme, but rare test, i.e., the worst-case test.

Current LD RDE boundary conditions are the result of lengthy discussions and many analyses, which do not have to be repeated. If the same principles are applied, the same outcome is to be expected. In particular, JRC (2017) deals with issues of cold starts and the relevance thereof based on the prevalence of cold start driving in normal use. Including the cold start in the 16 kilometres urban RDE evaluation was deemed appropriate, although on average one cold start occurs for every 22 kilometres driving from the data analysed by JRC. Over the course of 2014 to 2017 there have been several studies presented in the RDE-LDV expert group and later in the UNECE RDE informal working group on topics such as ambient temperature, altitude gain, and driving behaviour. Part of the material is available at the UNECE wiki [14]. The underlying principle has been that less than 3%-5% (i.e., "2-sigma") of the driving should be outside the RDE conditions, for each boundary condition separately. The analyses were very complex, dealing for example with representativeness of the data and quality of the signals. Moreover, the development of the WLTP had similar underlying analyses, where for example a Utility Factor was derived for PHEVs. If a vehicle can drive part of the trips after charging fully electric, it will lead to a proportional reduction of the number of cold starts, because it can be assumed that after charging a vehicle will have a cold start, once the engine turns on.

[14] https://wiki.unece.org/pages/viewpage.action?pageId=63308214

With the RDE-compliant vehicles entering the road, it has become clear that the remaining boundaries of RDE testing are still reasons for concern. Some RDE compliant vehicles that idle for longer than 5 minutes, which is the RDE boundary, show a sharp increase in NOx emissions. Likewise, NOx emissions at hard accelerations, above v*apos of 20 m2s-3 show disproportional increases in NOx emissions in a few tested vehicles. In a separate study for the Commission, the change of emission levels across the RDE boundaries was investigated. Performance of Euro-6d-temp vehicles in normal use is also investigated in TNO report 2020 R12024. Based on physical and technical arguments, proportional emission increases would be similar, or slightly less, than the increase in CO2 emissions associated with hard accelerations, high payload, or uphill driving. This has also been the underlying principle for the correction of emission data in RDE if the CO2 deviates significantly from the WLTP values[15]. Moving forward from RDE to EURO 7 has led to a change in principles. All common vehicle usages, observed on the road, also pulling trailers, or defrosting the windows by keeping the engine running for a longer period, are to be included in the EURO 7 testing. Even if these usages are less frequent as shown for example in the distribution of vehicle-km to temperature and altitude classes in Figure 6-3 (extreme temperature cases for Greece and North Finland are presented in Figure 6-4), large emission increases will make them still relevant, because the impact is based on frequency multiplied by the emission level. Moreover, some less frequent conditions, like cold temperatures, are more common in the winter in Nordic countries and the exclusion of these conditions from testing may lead to specific local, regional, and seasonal problems with air quality.

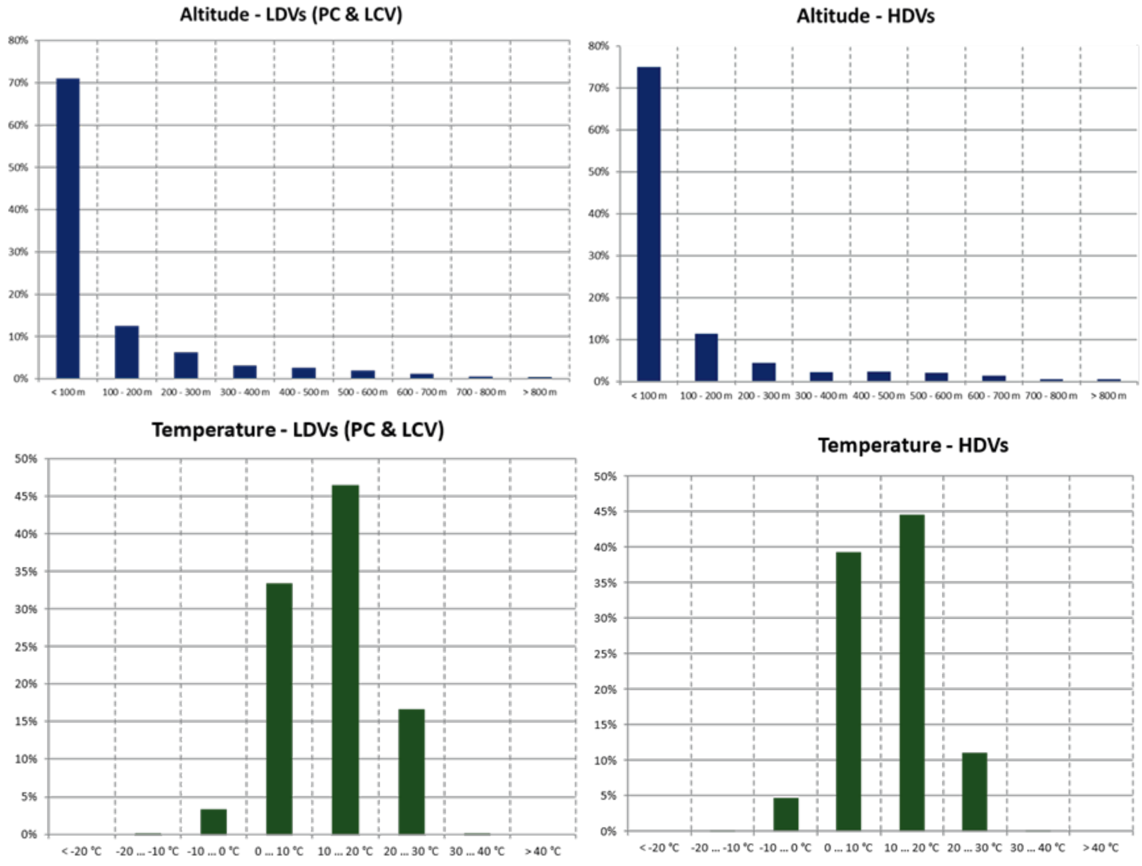


Figure 6-3: Distribution of vehicle-km (EU-27 for year 2010) to altitude and temperature classes for LDVs and HDVs (compiled from data by many different sources such as ACEA, Eurostat, DG MOVE statistical pocketbook)

[15] See also TNO (2019) for expected deviations and underlying reasons.

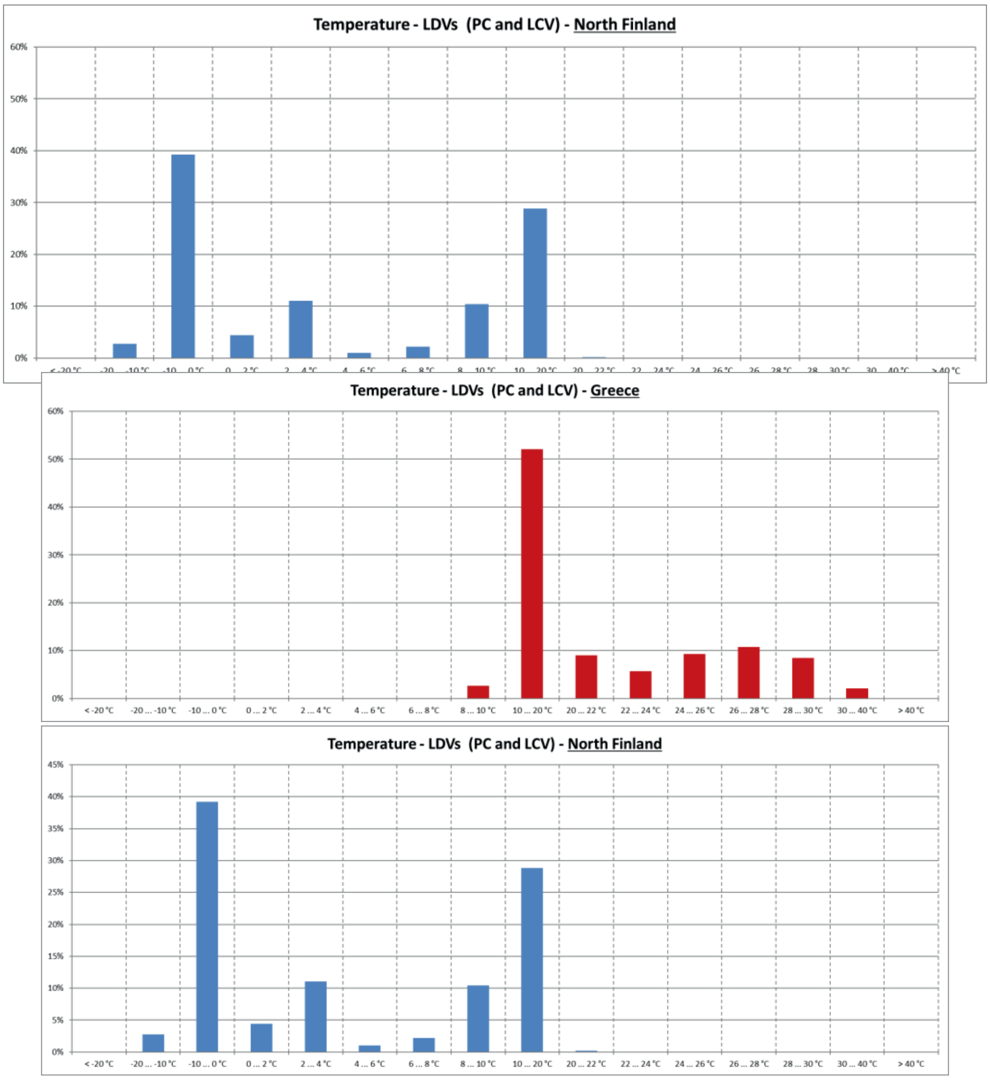


Figure 6-4: Distribution of vehicle-km (year 2010) to temperature classes for LDVs in Greece and North Finland (compiled from data by many different sources such as ACEA, Eurostat, DG MOVE statistical pocketbook)

In conclusion, it should not be assumed automatically that operation outside current Euro 6 and Euro VI test boundaries is extreme or rare. It should, however, be noticed that the frequency of conditions beyond the current RDE boundaries may significantly vary among the different vehicle/powertrain categories/types, countries, and temperature zones. The most eminent example is cold start emissions. It has been the case for many years that cold start emissions dominate the overall emission level of petrol cars. For diesel vehicles, a similar situation has arisen with the introduction of RDE testing. Currently, cold start emissions are implicitly regulated by a limit on the distance or work of the tests that include a cold start. For light duty vehicles, the urban evaluation of at least 16 km is the distance over which the cold start emissions can be spread, to remain on average below the limit for that urban phase. With many trips in normal use shorter than 16 km, especially in the urban environment, it is important to make sure that no disproportional emissions occur over shorter trips than 16 km (see for example JRC (2019). But a short cold start test, say 5 km, would then need to be linked to a higher emission limit value, about a factor of more than 3 times higher (this factor is discussed and justified with the analysis in Section 7.4), to be consistent with the performance of currently available emission control technologies. Currently, the urban evaluation of the RDE test, with a minimum distance of 16 km determines the stringency in terms of cold start emissions, which already includes several km of warm driving. Obviously, a method that would allow sufficient control of cold start emissions without offering disproportional margin for warm operation should be recommended. In section 4.2.4 it is shown that 60% to 90% of the emissions occur in the first few kilometres. Further driving with a warm engine and after-treatment systems adds distance, but little emissions.

Cold start emission performance would be further aggravated where there is high power demand while the catalyst is still cold. In normal use, the worst-case and highest emissions operation would correspond to a short test starting with a cold engine from sub-zero ambient temperature, with an aged vehicle under high power demand driving. Such a worst-case must be identified before an emission limit can be decided upon.

Apart from the cold start, there are many details relevant for emission testing, which eventually determine the actual stringency of the emission test together with the emission limit. An emission limit must always be seen in the context of the test conditions and boundaries. These details are discussed in this chapter with the underlying principle that there is only one single emission limit per emission component, in mg/km or mg/kWh, for all tests. Designing separate tests for different conditions was raised early on with the stakeholders but was not retained for two reasons. First, separate tests will increase the complexity of the legislation. Second, in the last twenty years it has been observed that test boundaries can lead to specific vehicle and engine design optimisation resulting in disproportional increases in emission outside the test boundary. Therefore, it was recommended that vehicles should comply with the emission limit in a wide range of tests, i.e., “any test”. However, normal use also includes, for some vehicles the pulling of trailers and caravans, or other special purposes, or rare weather conditions, or altitudes, that are typically observed only at the fringes of the wide range of European vehicle uses. So eventually, two emission limits: normal and extended are recommended, to cover all driving conditions observed on European roads.

Arguments to introduce test boundary conditions and restrict testing are wide and varied. Excluding less frequent vehicle usages and restricting the test to more normal driving and average conditions, discussed above, is only one argument. The high test burden, to cover all conditions in the testing, during engine development and assessment is also raised as a reason to restrict testing, for example, at higher altitudes. The driver influence, and the ability to produce high emissions by artificial driving during the test, is also given as a reason to apply rather generic restrictions. The high cost of emission control technologies to reduce emission in specific and rare circumstances is argued to introduce restrictions. Issues with safety, drivability and comfort are put forward as well to put boundaries on testing. On the other hand, environmental studies showing limited overall impact, or contribution, of vehicle emissions on the environmental problems in the future and at large are used also to argue the limited need for more stringent legislation. Eventually, one could still argue that if lower emissions can be achieved with limited effort and simple or proven technology, a more stringent limit can be set.

On the WLTP and the RDE tests low emission results are reported. However, some low emission results are not a guarantee that low results are obtained in all conditions, all test executions, and at all aging. EURO 7 is really about robustness of observed low emission results. Robustness is defined as good emission performance in a wide area of usage. Wide range testing is seldom exhaustive cover for all eventualities. Therefore, more generic arguments are needed to fill in the gaps in testing.

If a single limit applies to the tests, it will be essential to determine the test and the test conditions that lead to the elevated emissions. A second extended region of emission testing will allow for a broader coverage of vehicle use across Europe, retaining lower limits for more common, i.e., normal, driving. However, two test regimes will make the evaluation even more complex. A greater part of the testing described in this report addresses this question, with two types of tests: normal and extreme. The task is to set achievable emission limits.

Three parts of the RDE test should be considered in the evaluation.

1. First, test design: trip order, distance shares, payload, altitude gain, altitude, elevation difference, vehicle adaptions (trailer, roof box) and alternative vehicle usages.
2. Second, test execution: test duration, preconditioning, cold start driving, urban velocity, motorway velocity, urban stop share, stop times, v*apos, RPA, trip normality.
3. Finally, test conditions, of which ambient temperature is the key element.

Considering these elements of the RDE test, all elements restricting the test to have more reproducible or normalised results should be removed, as they are restrictions that may lead to unwanted optimisation not covering all normal use and any trip. These restrictions include trip order, distance shares, and stop time. They are to be removed, thus allowing specific shorter and longer trips that occur in normal use. Boundary conditions related to high engine power, such as altitude gain and $v*a_{pos}$[95%], are generally based on engine-out emissions, which increase with power and CO_2. For a modern vehicle the catalyst or filter removes the majority of the pollutant emissions and is often more effective at higher loads.

The results in section 4.2.4 show that low ambient temperature only leads to increases of the cold start emissions. Warm engine emissions are hardly affected by the ambient temperature. High power demand does lead to higher emissions, but the effect on cold start emissions is substantially larger.

Given that such a worst-case is covered with an appropriate selection of combination of an emission limit and a total test distance over which this limit is evaluated, all other cases of expected elevated emissions would be less challenging to control. In particular, if a “one limit fits all” approach is adopted (meaning a high numerical value for the limit is used) there seems little reason to tightly control emissions in the rest of the test, while the engine is warm. However, the spirit of any regulation should be that any elevation of emissions even over extreme conditions should not be more than the corresponding increase in power demand and fuel consumption. Proper engine tuning and properly sized emission control devices should be enforced to obtain such emission performance.

So, the issue arises on how to ensure low overall emissions during cold start and that tight control is also maintained under warm engine conditions, especially over urban use. An option would be to introduce two separate tests, or a separate evaluation of the worst-case cold start emissions in a longer test. This first would be based on a long test, i.e., 16 or 23 km, with few restrictions, and incorporating worst-case cold start conditions in this long test. A separate cold start test, of 5 km or even less, could then be mandated with higher emission limit and some reasonable restrictions on the power demand. The combination of two tests should be enough to cover all normal conditions. Such considerations would then be suitable both for LDV and HDV vehicles. However, two separate tests are not practical, and they do not contribute to the simplification of the approach. Instead, more flexibility in testing than what prescribed at Euro 6/VI today together with proper evaluation of cold start should be adopted at EURO 7.

The urban evaluation of the RDE test has been the first such practical attempt to ensure low emissions during cold start as a separate evaluation within a longer test. The HD MAW has had similar intentions to ensure low emissions in sub-sections of the complete test, including specific circumstances, but with the work-based evaluation method for heavy-duty and the neglection of low power windows, this has not been fully materialised. If the test can be dedicated to urban, rural, or motorway use, the need to provide an appropriate average over all conditions, which is a major hurdle in test execution, will also not be necessary anymore. For future testing more freedom to test any particular type of normal use will simplify the test protocol and the evaluation.

The shift of regulatory focus to independent on-road testing and in-service conformity testing, started with Euro 6/VI, allows for the possibility to extend the provisions to guarantee life-time compliance. In principle, the proper emission performance of the vehicle as a whole in normal use, should be the goal of any emission control legislation. Any separate evaluation of parts, systems, or functions is introduced so that it is made sure that each of these components functions properly but cannot independently verify that the real-world emissions of the vehicle remain under control. In a sense, this is part of the same general issue that a vehicle may satisfy all the requirements and pass all the dedicated tests but still result in high emissions on the road under specific operation conditions. Requirements and tests directly linked to complete lifetime and all normal use of actual vehicles on the road is the only method to guarantee acceptable emission performance. Therefore, on-road normal use testing should be the standard for new legislation.

New pollutants should be incorporated as much as possible in on-road testing. With many sensors and safety systems integrated on a vehicle, vehicles need special settings and treatment to be tested in the laboratory. This does not only entail the risk for an (possibly inadvertent) alteration of the operation of emission control, but it also makes it difficult for independent third parties to make appropriate testing in the laboratory without the participation of the manufacturer. On-road emission measurement systems should be enhanced, e.g., by introducing multi-spectral detection technologies, to facilitate measurement of an enlarged number of pollutants during on-road testing. Such major adaptions of PEMS may improve measurement quality and sensitivity over currently used systems and will make on-road tests the only method for emission evaluation, without the need to conduct additional laboratory tests.

Light commercial vehicles (N1), typically with larger frontal area and higher mass than passenger cars (M1), have had higher emission limits to date. Also, introduction dates and test protocols have exhibited differences between M1 and N1 vehicles. With RDE and WLTP introduction, some harmonisation has occurred. However, it could be argued that in the wider harmonisation of light-duty and heavy-duty vehicles emissions control regulation, with comparable stringencies, the light commercial vehicles are the bridge and these should be specifically considered in designing proper testing approaches. These are vehicles with a high mass and a low engine power, similar to heavy duty vehicles with engine powers below 35 kW/ton.

6.2 Specific testing recommendations for light duty vehicles

With the general concepts presented above, to satisfactorily control emissions both under low-power conditions with a warm engine in longer trips and worst-case conditions of a short trip with a cold start, there still remain some specific issues for light-duty vehicles. A specific issue of concern relates to high-power operation, which is currently not regulated in the RDE test. Only a small fraction of hard accelerations is allowed in RDE testing, such as extensive uphill driving, pulling trailers, and harsh accelerations. For heavy-duty trucks full load operation is satisfactorily covered. Moreover, heavy duty trucks seem to perform best in terms of NOx emissions in high power situations, at least in terms of g/kWh, because this corresponds to good temperature in sufficiently large catalysts. In contrary, PN emissions may rise considerably in long high-load phases due to continuous passive DPF regeneration that may consume the soot in the filter and can lead to a reduced filtration efficiency. If light-duty vehicles have appropriately sized catalysts, for the engine power and vehicle capabilities, including extreme operation, there should be less reason to exclude normal high-power operation that each vehicle is advertised to be capable of. An exception will always be the cold start, as a combination of high power and cold start will lead to higher emissions with limited emission control possibilities to control them during the first seconds of operation. On the contrary, the altitude gain and the $v{*}a_{pos}[95\%]$ boundaries may not be needed if catalysts are properly sized and engine tuning has been meticulously performed.

The maximum altitude boundary in RDE is related to the lower air density and reduced oxygen content in the combustion chamber as height increases. This is, in principle, not so much an issue of higher NOx emissions, but rather of reduced maximum engine output power. This is aggravated somewhat by higher ambient temperatures which also reduce air density and therefore oxygen availability in the cylinder. Retaining the same power output may then come at a cost of higher pollutant emissions because of combustion adjustment. However, such flexibility trade-offs should not be acceptable anymore, and somewhat lower power output at higher altitudes, above 2000 metres, could be an alternative option to be considered, rather than relaxed emission control. It has been argued that this will lead to safety issues, because of driver anticipation of a given vehicle power output, but this is similar to the perceived power reduction due to a road incline or strong headwind. There is limited test data available on the effect of high-altitude operation, the data that is available seems to suggest limited effects on emissions.

The emission limit in mg/km does restrict the minimum velocity this could be achieved at. As it was pointed out above, for idling alone, no emission limit in mg/km can be set. With a minimum acceptable distance, a limit can be set, but the issue remains that, for example with a minimum distance of as low as 5 kilometres in a two-hour test, this will still allow for substantial idling. Instead of a minimum average velocity, a maximal test duration for a short distance test is argued for. With the universal use of catalysts which require sufficient heat, the idling emissions have become a benchmark for good thermal management to ensure robust emission control. Ensuring low idling emissions should receive separate consideration both in light-duty and heavy-duty legislation.

Artificial vehicle driving not representative of real-world operation, such as extreme driving that may be attempted during an ISC test, has been signalled as a concern by the manufacturers. Revealing all potential loopholes in satisfactory emission control cannot be properly done in a single test procedure. An attempt to do so would also likely exclude valid normal driving and would complicate the test execution to consider a test valid, with the risk of invalidation. It is not rare that RDE tests are judged invalid due to inappropriate driving behaviour if more demanding tests, closer to the RDE boundaries, are attempted. A different approach should be introduced where the failure of the emission control due to extreme driving events (abusive artificial operation) is reported by the vehicle. This is somewhat similar to the AES declaration (manufacturer technical declaration of an Auxiliary Emission Strategy), but this should be made in a more transparent way and in real time, thus allowing the assessment of the frequency of such ‘AES’ conditions in normal use.

In essence, the current recommendation is not a large departure from the existing RDE legislation. Elements that restrict emission testing in any normal trip are to be removed, and the extended region in RDE is taken as the basis. Boundaries, for which there is little evidence vehicles cannot perform well, and those where vehicles have shown to have little problem, are to be removed or extended to extend the coverage of all normal European driving. Moreover, other normal, yet more rare, operation is included in the extended testing, with a higher limit.

Two parts of the emission test lead to high emissions, which have their own dependencies:

1. Cold start emissions: aggravated by low ambient temperature, high engine power, and aging
2. Warm engine driving emissions: aggravated by high engine load, and aging.

Normal and extreme engine loads can, for example, be inferred from typical and high fuel consumption. Towing caravans and trailers can double the fuel consumption. Driving uphill and high payload, and aerodynamics adaptions add to the engine load too, depending on the trip and driving.

Special exception should be made for low mileages, as, for example, the DPF will function only properly after a few thousand kilometres, once a soot layer is formed.

Within the existing relevant boundary conditions, in many cases the extreme boundary with the factor 1.6 are carried over from the current RDE legislation (RDE4). The minimum distance is therefore 16 kilometres (from urban evaluation), the temperature is set at the range -7 °C to 35 °C. Only the maximum altitude is increased from 1 300 metres in the extended conditions to 1 600 metres, since little evidence exists to demonstrate that altitude is a fundamental or technical problem for emission control technologies. For the same reason, the maximum velocity is increased from 145 km/h to 160 km/h.

A single new boundary condition is introduced, related to the worst-case test conditions and execution. Since the cold start is aggravated at low ambient temperatures and high engine loads, the engine power in the normal conditions is restricted during the first two kilometres. From the results in chapter 4 it is clear that cold starts last at most until two kilometres but can be much shorter. So, for any time interval from the start until the first two kilometres are completed, the average power should remain below 20% of the rated power. In the extended test regime this restriction is lifted, and also high engine loads at the cold start are covered in this case with a higher associated limit.

The recommendation for the new extended limits is an extension to cover all of European usages and conditions. The associated limits are altitudes up to 2 200 metres, typical of high Alpine passes; and the -10 °C to 45 °C temperature range, incorporating high temperatures observed regularly in the summer. The low temperatures have been raised as an issue of an aggravating factor in the worst-case, cold start test. The increases in the cold start emissions, as observed in Chapter 4, with lower temperatures led to a slightly moderate extended condition down to -10 °C. The remaining boundaries are not a large deviation from current RDE in normal conditions, except for the maximal mileage which is raised from 100 000 km/5 years to 240 000 km/15 years, to reflect the normal useful life of modern vehicles.

However, the current recommendation (Table 6-1) is an extension over the existing RDE legislation in many different ways, related to the boundaries that are removed. Currently, many characteristics related to the use of the vehicle, such as higher power demand, dynamic driving, or a sense of trip normality linked to the WLTP, limit the coverage of normal use unnecessarily. Therefore, the following boundaries in current RDE are no longer deemed relevant as requirements: average velocity in urban driving, maximal idling period, maximal idling fraction, accumulated altitude gain, net altitude gain, trip order, distance shares, minimal distance, trip duration, trip normality based on the CO_2 compared to the WLTP CO_2 values, moderate driving as in minimal RPA, and dynamic driving as in $v*a_{pos}$[95%]. Likewise, the restrictions during the cold start are not deemed relevant, and replaced by the power restriction, which limits the engine out emissions before the catalyst reaches operation temperatures.

Table 6-1: Recommended testing and evaluation boundaries for normal and extended conditions

Parameter	Normal	Extended
Minimal evaluation distance	16 km	16 km
Trip and driving	Any	Any
Ambient temperature	-7°C to 35 °C	-10°C to 45 °C
Altitude	1 600 m	2 200 m

Minimum mileage	3 000 km	Any
Maximum velocity	<160 km/h	speed limit
Towing/roof box/etc.	None	Included
Cold start power restriction	up to 2 km	None

Apart from the testing boundaries, the durability demands also need to be defined in the legislation, i.e., the age and/or mileage, up to which the vehicle has to meet the limits. The recommendation is to increase EURO 7 durability requirements compared to EURO 6, as presented in Table 6-2 for normal and extended conditions.

Table 6-2: Recommended durability requirements for normal and extended conditions

Parameter	Normal	Extended
Maximum age or mileage	240 000 km/15 years	240 000 km/15 years

The extension, like ambient temperature, and removal of boundaries, like v*apos, is motivated, in part, by the observation that Euro-6d vehicles perform very well in these conditions, and there is little technical or physical reason to retain these boundaries. See the results in Chapter 4. The low prevalence of certain operation conditions or vehicle use is no reason not to apply robust emission control technology, with similar hardware, to cover these conditions. Cold start and aging are recognised as a technical problem and a risk, respectively, and analysed in detail.

Any normal trip should be a valid test trip, with two rules applied, to arrive at the emission limit.

1. First, the emission limit itself is roughly based on the worst-case tests with a warm engine and exhaust emission control suitable for long distances such as a motorway test. The much higher normal cold start emissions are therefore linked to a minimal evaluation distance of 16 kilometres, to spread the cold start emissions, or budget, to the same level of the emission limit, derived from the warm tests. This set the emission limit and cold start budget for the normal conditions. The extended conditions incorporate all other vehicle uses, but this limit is the result of the worst-case cold start test. Extreme dynamics cold start emissions, roughly based on the worst-case tests, are mainly the result of high-power demand in the first kilometres, and therefore placed in extended conditions.
2. Second, special vehicle use, within the advertised specification, like towing heavy trailers, are also placed in the extended conditions, as are higher altitudes and more extreme ambient temperatures. The emissions in these cases are expected to be proportional to the fuel consumption increase, which is less than the increases observed in the extreme dynamics cold start test, in cold conditions.

The remaining restriction on cold start in normal conditions of use should be based on the power demand and engine out emissions before the exhaust emission control system (EATS) is heated up. In this period of warm-up directly after a cold start the tailpipe pollutant emissions are strongly dependent on the raw emissions of the internal combustion engine. There are two key factors that influence the raw emissions before the EATS is warmed up and the catalytic conversion effectively reduces the pollutant emissions. The first part is the pollutant emission concentration in the exhaust gas, mainly defined by the quality of the combustion process after cold start. This is a continuous development goal and best available engines show a very good behaviour (chapter 4). The second aspect is the exhaust emission mass flow (which defines the residence time in the catalyst) which is mainly influenced by the power output.

Under normal conditions of use the normalised power output of the combustion engine (used power divided by maximum power) is low since most of normal driving situations start with parking, low load driving and moderate acceleration in urban areas. Nevertheless, very high-power demand can happen in extended conditions including trailer towing or uphill accelerations.

The EATS can be warmed up very efficiently by waste heat from the combustion engine including engine heating measures without strongly increasing fuel consumption and CO_2 emissions. Another possibility is the direct catalyst heating with fuel burner or electrically heated catalysts with limited power (up to 6 kW). Engine catalyst heating leads to warm-up of the EATS normally within the first 2 km of the driving after cold start under the suggested EURO 7 temperature boundary conditions of normal use (-7°C to 35°C). The warm-up distance of up to 2 km is therefore a relatively constant characteristic value. Low load driving at low-speed results in low exhaust enthalpy and longer time for warm-up but also with low raw emissions. High load driving results in high exhaust enthalpy with faster warm-up and higher raw emissions but also faster driving speed.

Extreme testing conditions discussed in chapter 4, leading to high emissions, exhibited increased emissions of some cycles in combination with the cold start. The key aspect of these cycles and tests is the power demand, compared to the rated engine power. To propose a low emission limit in normal use given these cold start emissions, some restrictions of engine power should be included. The engine power in the first seconds, for petrol vehicles, to first minutes, for diesel vehicles, is single evaluation criteria. The growing window average power, i.e., the average engine power up to a certain time is recommended for evaluation. For each time window up to 2 kilometres, the average power should remain below a certain fraction of the rated engine power. Since engine power is generally not known, instead the work, based on test mass, velocity, and altitude gain can be used to determine work and power at the wheels. An alternative approach would be CO_2 based, where the average CO_2 rate over any segment from the start up to 2 kilometres should remain roughly below CO_2 [g/s] < 0.03 * P_{rated}[kW]

The driving power of a vehicle must overcome rolling resistance, grade resistance during uphill driving, inertia (acceleration resistance) and air resistance or aerodynamic drag. In most driving situations after cold start the power necessary to overcome air and rolling resistance is very low compared to the acceleration power and climbing power. Figure 6-5 gives an illustrative example of this calculation and the relative positioning of the different driving resistances. Hence it can be deduced that for simplification the air and the rolling resistances can be neglected in an approximate but accurate calculation.

Therefore, the instantaneous (calculations at 1 Hz) approximated driving power can be calculated as follows:

$$P_{driving}\,[W] = (1.07 * m * a + 9.81 * m * \sin\alpha) * v$$

where $P_{driving}$ is the instantaneous power, m is the test mass of the vehicle in kilograms, v the velocity in meters per second, a is the acceleration in metres per second square and α is the angle of inclination in degrees. It should be noted that negative values of $P_{driving}$ are zeroed. The factor of 1.07 is added so that the inertia of the rotating masses is taken into account.

Then the power metric is calculated based on the following equation:

$$PowerMetric = \frac{P_{average}}{P_{rated_{vehicle}}} = \frac{\frac{\sum_1^{t_n}(P_{driving,tn} * \Delta t)}{t_n}}{P_{rated_{vehile}}}$$

With: Δt=1s, $t_n = 1 \div t_{n,max}$ and $t_{n,max}$ the time that corresponds to 2 km driven distance.

The power metric is calculated for bins from 1s to $t_{n,max}$, with 1s step, until 2 km, i.e. for the bins 1-2s, 1-3s, 1-4s, …, 1-$t_{n,max}$. For each bin the cumulative positive energy $\sum_1^{t_n}(P_{driving,tn} * \Delta t)$ is calculated and divided with the cumulative time (t_n). Then, this is normalised with the rated power of the vehicle. Finally, the maximum value among the bins is taken to identify if this test falls into the normal or extended conditions. In most normal cases this maximum value is detected in the first accelerations of the cycle, but this of course depends on the exact driving conditions (such as velocity profile, road gradient etc.).

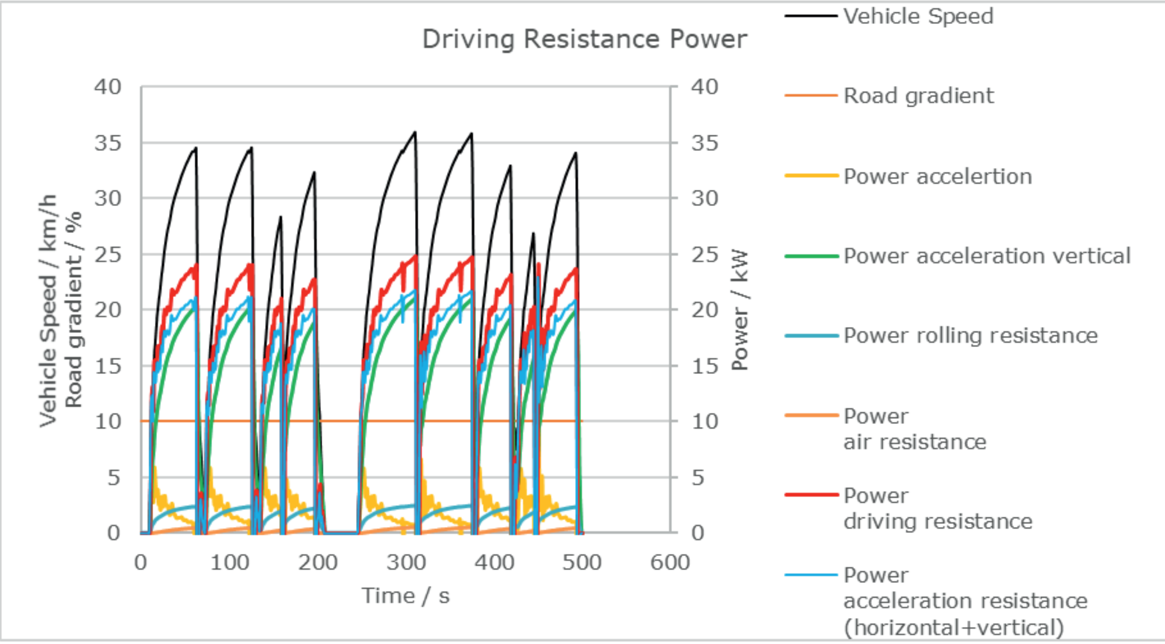


Figure 6-5: Power necessary to overcome the different types of driving resistances over a speed profile at constant 10% gradient

For the tailpipe emission performance under normal conditions of use the driving power is a good indicator to define a threshold between normal conditions of use and extended conditions of use. Normal driving is additionally dependent on the maximum power of the vehicle. Powerful vehicles are able to accelerate faster and drive faster uphill and this also changes the driving behaviour for most drivers. With more powerful cars, normal driving style is faster with higher power demand.

Therefore, a threshold between normal conditions of use and extended conditions of use should consider the maximum continuous power of the vehicle. Continuous power in this case means the vehicle driving power that can be delivered without time restrictions.

According to these assumptions and boundary conditions a threshold of the power metric for the first 2 km of a trip is recommended to be used. The recommended (see also discussion in Figure 6-10) threshold is 15% of the rated power of the vehicle: $P_{average} < 0.15 * P_{rated}$.

Normally, drivers do not drive away immediately after the engine start and certainly not at full throttle. There is limited information on driving behaviour directly after the start, but the general experience is that in the first minutes the power demand is limited.

Figure 6-6 and Figure 6-7 show the calculated normalised driving power in the WLTC for 2 vehicles, a mid-size sedan (BMW 520i) and an LCV (VW Crafter) respectively. The figures show that the mid-size car uses up to 5% of the maximum power as average in this cycle while the LCV used approx. 10%.

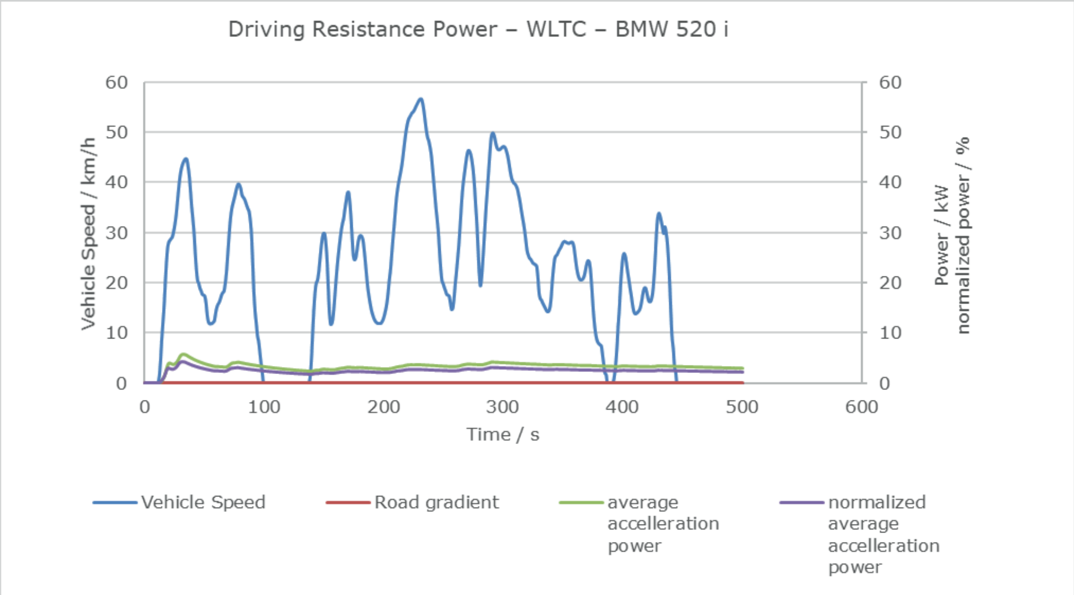


Figure 6-6: Driving resistance power over WLTC for a BMW520i

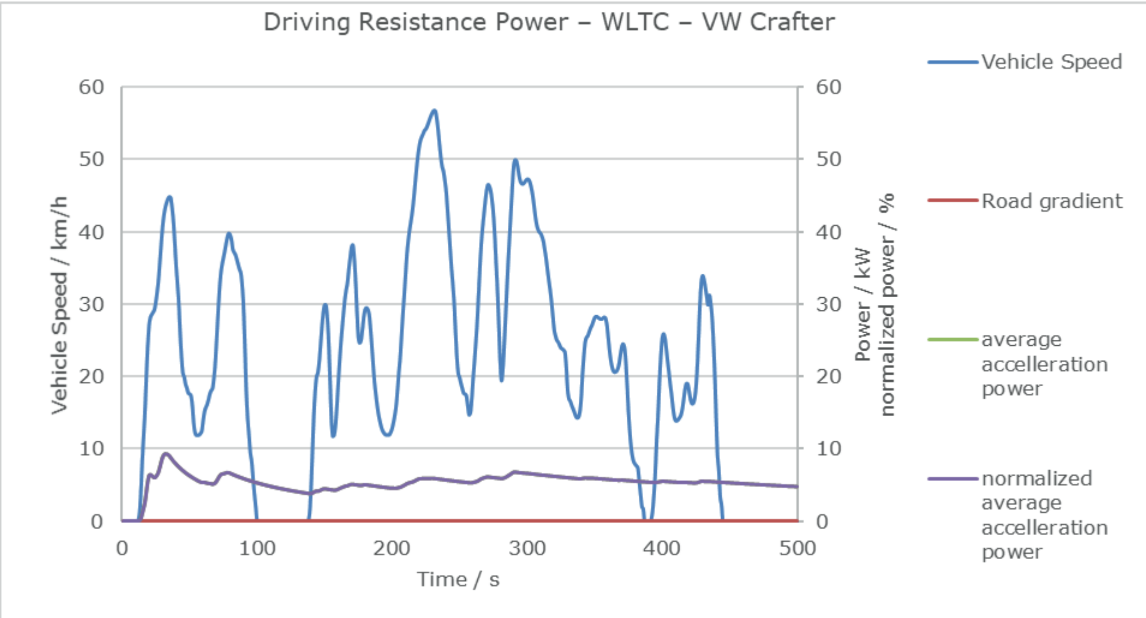


Figure 6-7: Driving resistance power over WLTC for a VW Crafter

In a demanding so called “worst-case” EU6d RDE cycle the power demand in the first 2km is 28% for the mid-size car and 62% for the LCV (shown in Figure 6-8 and Figure 6-9 respectively), based on the vehicle capability to accelerate.

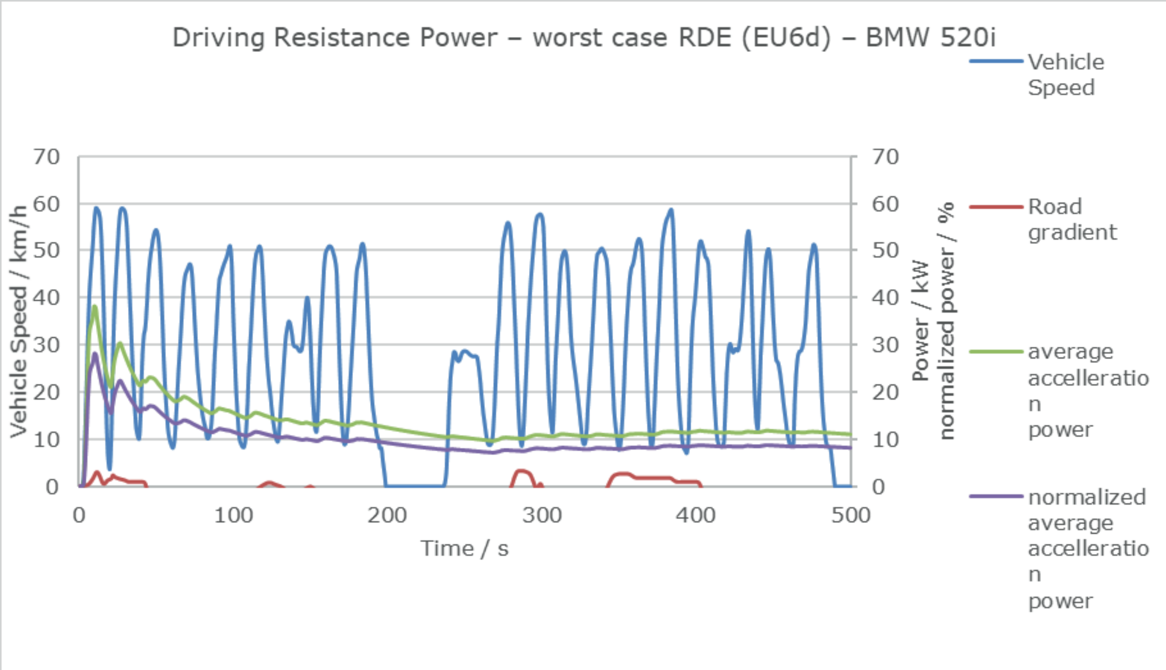


Figure 6-8: Driving resistance power over the Euro6 worst-case RDE for a BMW 520i. The maximum average power P[kW] is reached at the end of the first acceleration.

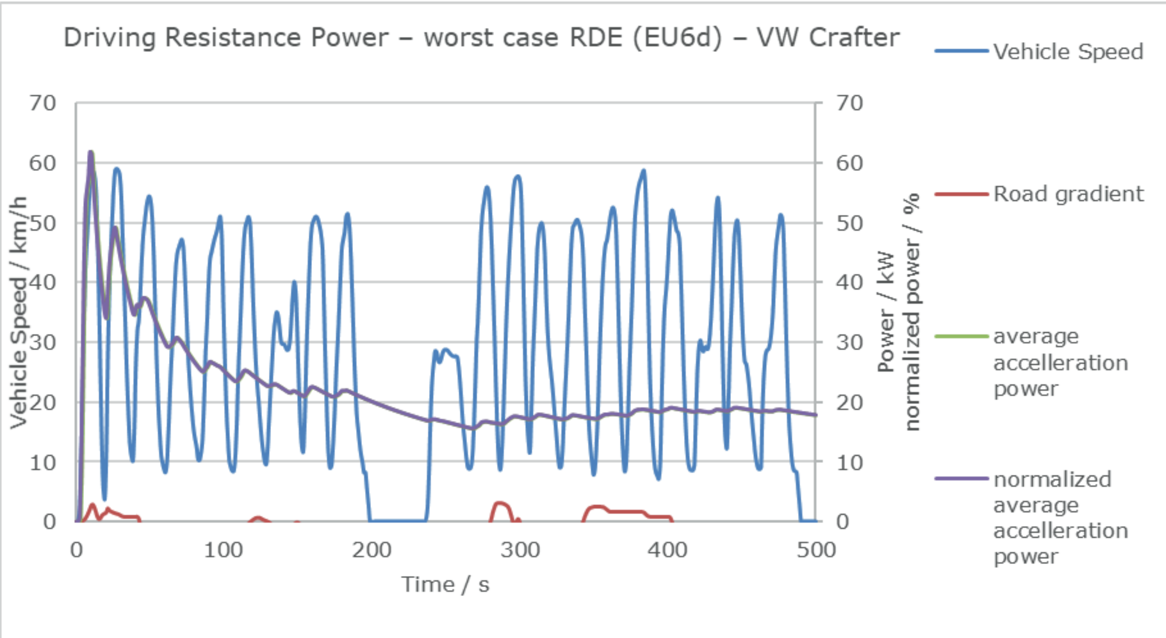


Figure 6-9: Driving resistance power over the Euro6 worst-case RDE for a VW Crafter

Nearly all the moderate on road measured driving cycles from the CLOVE investigations use less than 15% of the maximum normalised driving power in the first 2 km after cold start, as shown in Figure 6-10. Hence, it is recommended **for a valid RDE under normal driving conditions** to limit the maximum normalised driving power in the first 2 km after cold start at 15%.

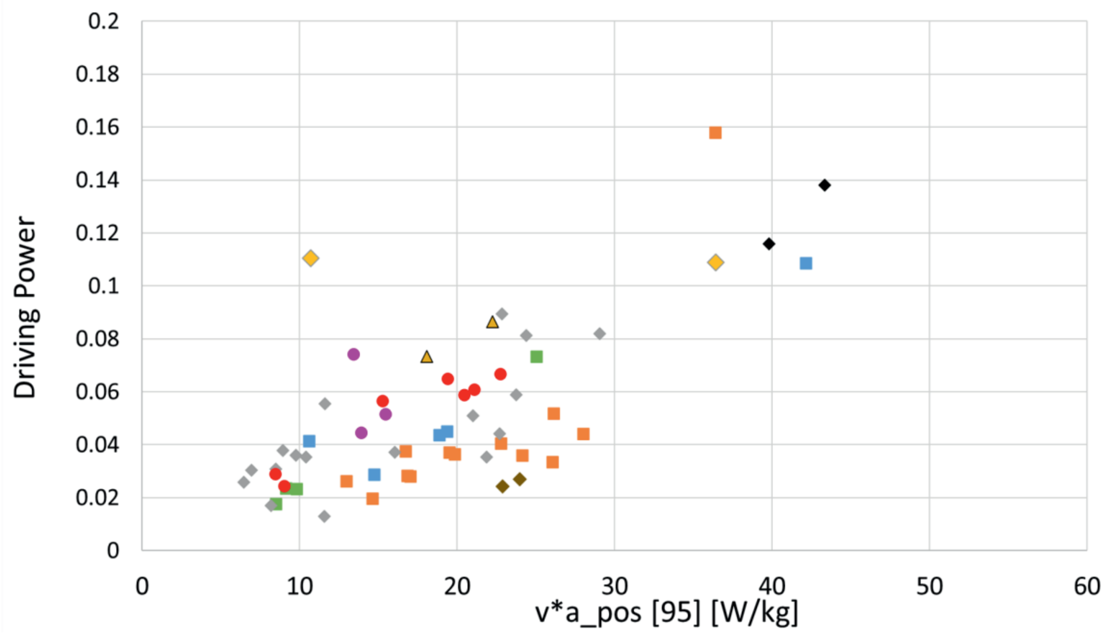


Figure 6-10: Normalised driving power (over maximum power) as functions of a v*a pos [95%] for a variety of driving cycles and vehicles from the CLOVE database

The 16 kilometres for the cold start budget could be an optimisation problem, for a single emission limit, similar to the utility factor (UF) of PHEV evaluation, that incorporates trips of different lengths, if total emissions are key. On the other hand, cold start emissions are usually urban emissions, with larger environmental impacts. So, cold start emissions require special attention not achieved by optimising on the total emissions alone. The achievable emission levels associated with cold start should be explicitly factored in a decision of the emission limit and test distance. As a reference, Figure 6-11 presents the distribution of average trip length for passenger and commercial vehicles in indicative European cities.

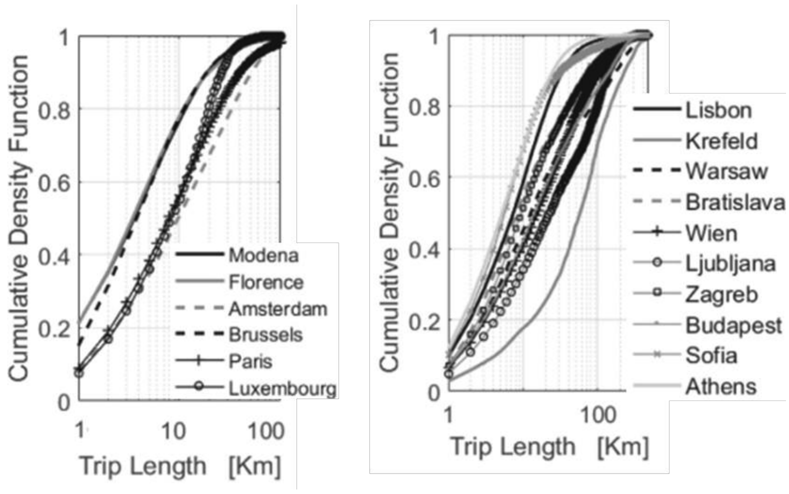


Figure 6-11: Distribution of average trip length for passenger and commercial vehicles in indicative European cities (Paffumi, et al., 2018)

A short distance will lead to a more dedicated cold start test, but with a higher limit. A long distance will combine cold start and warm engine emissions in a single test, but with a lower emission limit. Separating the items in two tests will require much more precise test description, which will likely need to exclude certain normal trips, variations in cold starts and vehicle uses. It seems likely that the cold start emissions will start to dominate the overall emissions for modern vehicles. Given the emission limit based on the distance driven combined with the test distance, combined into an emission budget, is just another way to look at this. Warm emissions are generally much lower, but removing the boundary conditions, to include all trips is mainly a robust emission control problem, for which some leniency is given for the risks of incidents of high emissions in special circumstances.

6.3 Specific testing recommendations for heavy duty vehicles

Many test conditions can be aligned between HDVs and LDVs. Such an alignment is also relevant to have comparable demands for heavy LDVs (close to 3.5t TPMLM) and smaller HDVs (3.5 to 5t TPMLM).

However, some unique features should be considered when defining test conditions for HDVs. To be considered are other existing regulations, the variability in HDV emissions and the corresponding manufacturing processes, division of work and responsibilities.

Regulation (EU) 2017/2400 defines the test conditions for CO_2 emission declaration. According to this regulation the components relevant for vehicle efficiency are measured and certified as systems, components, or separate technical units. The engine test procedure also monitors pollutant emissions. Consequently, the test procedures needed by regulation EU 2017/2400 should also be kept in EURO 7, unless the CO_2 determination methods are amended. Without such a basis for the engine tests, Regulation (EU) 2017/2400 would need to be heavily revised to cover all test procedures yet defined according to Regulation (EU) 582/2011. Furthermore, it is also recommended to measure and limit pollutant emissions in the relevant CO_2 and fuel efficiency test procedures to avoid test specific optimisations for best fuel efficiency without NOx limits in the engine tests. Thus, the following engine test procedures need to be included in EURO 7: WHTC, WHSC, FCMC (Fuel Consumption Mapping Cycle) and the full load curve measurement.

Regulation EU 2017/2400 also defines a vehicle test to verify the results of the component tests and vehicle modelling by VECTO, i.e., the VTP test (Verification Test Procedure). Currently the demands of the VTP are not in line with the boundary conditions of ISC vehicle tests in Euro VI. To ensure these specific optimisations of the engine and emission control systems in the VTP test conditions towards highest fuel efficiency but increased pollutant emission levels are not possible, it seems to be reasonable to allow a combined VTP and RDE test in the future. A main difference in test conditions is the shorter test time in the VTP to limit the drift of the wheel torque measurement devices. Furthermore, the VTP currently is applicable only to new vehicles as a COP test. To also allow emissions testing against an applicable regulation during VTP tests, it would be needed to:

- Reduce the test distances for on-board emissions testing (currently necessitating minimum 4 times the WHTC work typically corresponding to more than 3 hours testing) to cover tests as short as 80 minutes test durations.
- Extend the minimum odometer reading of HDVs for on-board emission tests down to ca. 5000 km.

These above are in line with the general tasks to introduce RDE testing over a wider range of test boundaries for HDVs. The current ISC checks the conformity during on-road driving with the WHTC test and analyses the 90th percentile of moving average windows (MAWs) representing similar work as the WHTC. For shorter tests, especially if cold starts are included, the statistical method does not seem to be very robust. Furthermore, the current (EURO VI E) MAW method does not cover low load conditions very well, since MAWs below 10% of the rated power are excluded, and 90% of all MAWs are used. From exclusion of the cold start and low load driving in ISC evaluation up to EURO VI D we identified rather high emissions in such driving conditions from several HDVs which still met the Euro VI limits. Thus, for EURO 7:

- All engine loads should lead to a valid test.
- Emissions should be evaluated from the test start onwards.

This leads to the set of testing conditions recommended for EURO 7 HDVs shown in Table 6-1. The corresponding evaluation methods and limit values are described in chapter 8.

Table 6-3: Recommended testing conditions for EURO 7 HDVs (normal and extended conditions)

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Ambient temperature	-7°C to 35°C	-7°C to 35°C	-10°C to +45°C [a]
Cold start	Evaluation from $t_{coolant}$ > 30°C on; cold start weighted with 14%	Test evaluation from engine start on; extra limits for cold start	Test evaluation from engine start on; extra limits for cold start
Auxiliaries use	None	Possible as per normal use	Possible as per normal use
Min Trip duration	> 4 x WHTC work	any [b]	any [b]
Evaluation	1 WHTC window	Ref. work, ref power method [c]	"Extension Factor [d]"
Engine load [kW/kW$_{rated}$]	Only work windows > 10% valid	Any [e]	Any [e]
Payload	10-100 %	0%-100% [f]	0%-100% [f]
Max. altitude [m]	1600 m	1600 m	2200m
Trip composition	Depending on class of vehicle	Normal trip as intended usage	Normal trip as intended usage
Minimum km before testing	15 000 km (>60 hours)	3 000 km for <16t TPMLM 6 000 km for > 16t TPMLM	All > 300 km

[a]: Extra provision for maximum AdBlue defrosting time suggested for lower temperatures.
[b]: In combination with the "Budget" Limit approach described in chapter 5, no minimum test time is required.
[c]: The details of the recommended evaluation method are described in chapter 8.
[d]: For a simple regulation, for the time driven in the extended conditions range, the measured emissions shall be divided by 2, independent of how many of the parameters are in the extended range. The "time" refers to 1 Hz recorded signals after time alignment of emissions and corresponding test conditions.
[e]: With reference power method
[f]: Values show allowed range, the minimum payload results from weight of driver and test equipment.

Beside the boundaries for the test conditions, the durability requirements also need to be defined, i.e. the age and/or mileage up to which the vehicle has to meet the limits in on-road emission tests. According to the findings in chapter 5.1, the recommendation is to extend the age and cumulated mileage where vehicles must comply with limits in tests compared to EURO VI. Maximum mileages found in registration in EU countries are in the range of 1.3 million km for articulated trucks and around 0.8 million km for small rigid trucks. These high cumulative mileages are found typically at very old vehicles, which have then quite low yearly mileages and low shares in the vehicle stock and thus do not contribute significantly to vehicle mileages on the road. A recent evaluation of data from yearly HDV inspections in Austria and Germany show, for example, ca. 1% share of articulated trucks (N3 > 16t) with an age of more than 20 years and a mileage of more than 1 million km (www.hbefa.net). A proposal for the range of useful life for EURO 7 is shown in Table 6-4.

While compliance with emission limits may not be demanded for very old vehicles, to allow lower limit values for the majority of HDVs on the road, OBD functionalities should be fulfilled at any vehicle age to identify relevant failures of emission relevant components.

Table 6-4: Recommended useful life for EURO 7 HDVs

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Durability [km]	N2, N3<16t, M3: 300k km N3 > 16t: 700k km	N2, N3<16t, M3: 700k km N3 > 16t: 1,200k km	N2, N3<16t, M3: 700k km N3 > 16t: 1,200k km

Note: The durability of the emission control systems until the end of their lifetime will be dealt with separately

6.4 Units recommended for HDV limits

Beside the demands for HDV testing, selecting the units for the emission limits needs to accommodate different boundary conditions to passenger cars. HDVs are designed for a broad range of missions, such as small and large city buses, municipal utility trucks, HDVs used on construction sites, and long-haul goods transport. The weight of the trucks ranges from 3.5t TPMLM up to 60 tonnes in some northern countries and auxiliary power demand can vary between a few kW for alternator, air compressor, HVAC up to more than 50 kW for special power take off devices (PTO) such as garbage compressors.

Consequently, a common limit in g/km is not reasonable: if 60t trucks had to meet such a limit, the same limit would be insufficiently stringent for small trucks. Furthermore, introducing different limits per size class would lead to complex regulation. The following options were considered in more detail:

g/kWh........ the unit currently used accounts for the very different engine work needed for the various missions of the wide size range of HDVs, which impacts on the resulting emission mass flows. The unit also supports the engine tests on the engine dynamometer, which will remain relevant also for EURO 7 as explained before. The disadvantage of the unit is the need to measure instantaneous engine power during on-vehicle tests. This value is available via OBD interfaces and has been used successfully since 2013. For EURO 7 an independent verification of this signal could be implemented in the VTP test based on the data already available from the CO_2 verification of HDVs. Finally, the unit also supports responsibilities in multistage type approval processes, where engine manufacturers can be different to the vehicle manufacturers. While EURO 7 may limit vehicle emissions instead of engine emissions, the engine manufacturer will be responsible to the vehicle manufacturer rather for emissions per engine work since the OEM cannot influence the technology downstream of the engine which can heavily influence the work needed per km. Engine manufacturers can also directly control the g/kWh for OBD and OBM tasks.

g/MJ fuel..... similar to the current g/kWh but fuel flow can be measured via carbon balance with PEMS instruments independently. The disadvantage is the fact that fuel efficient engines would have lower absolute emission allowances.

g/GVW-t-km with GVW (Gross vehicle weight) being the mass of vehicle and loading as weighted at the emission test. Since the kWh are correlated to the GVW-t-km under normal driving, the unit seems to be the most suited of the “per kilometre” based options. However, the analysis showed that the kWh/GVW-t-km approximately doubles from 40t tractor trailers towards smaller distribution trucks. In addition, the use of PTOs can more than double the engine work per kilometre. If the altitude difference allowed between test start and end in future RDE tests was not defined to be close to zero, the high mass of HDVs would add a significant further impact on the kWh/GVW-t-km. Assuming similarly optimised emission control technologies in EURO 7 for all of these HDVs, the emissions in g/kWh would be similar; consequently, increasing kWh/GVW-t-km demands have proportional impact on the emission levels in g/GVW-t-km. To introduce a fair emission limit regime for all HDV (3.5 to 60 t TPMLM) which also allows tests of e.g., garbage trucks during collection and city buses in hot conditions having both high PTO work demand, would thus be complex. It seems to need a large set of correction functions or quite narrow boundaries for test conditions to provide equally demanding conditions for all HDV categories. The advantage of the unit g/GVW-t-km is that the vehicle emission test can be performed without the need for measuring engine work. This benefit, however, does not seem to outweigh the risk of producing more complicated or unfair emission limit provisions.

There are several other pros and cons, but so far, we see major advantages for the g/kWh unit in terms of setting up simple and fair emission limits for HDVs. **Thus, it is recommended to keep the g/kWh unit for EURO 7.**

7 Recommended EURO 7 limits and technologies to meet them for cars and vans (LDVs)

Meeting the challenges of post-Euro 6/VI standards will require, more than ever, a system-wide approach to be applied to ensure robust emissions control of both regulated and unregulated emissions species. The vehicle systems, powertrain (both ICE and hybrid system) and exhaust emission control system will need to be fully optimised and robust to interactions, such as engine off and on events, to deliver low emissions under normal operation.

The regulation of additional exhaust pollutant species, which can be formed in part in the catalyst systems employed to meet Euro 6/VI standards, creates an additional challenge. Emission reductions for currently regulated pollutants must be ensured, while also limiting any increase in emissions of pollutants that are also considered for inclusion in EURO 7. The challenge of determining an acceptable final vehicle calibration against the range of engine operational parameters is significantly increased by the increased range of emissions species controlled and expanded boundary conditions of operation to validate, as well as the reduced limits of currently regulated emissions species. Hence a new approach of calibration may be required, including updated range settings for example in the design of experiments for calibration development.

With respect to the findings of Chapter 4, where the emissions performance of the vehicles and technologies currently in the market has been analysed (Figure 2-1, Step 2), the objective of this Chapter is to examine potential future technology packages (Figure 2-1, Step 3) considered effective for EURO 7 and to assess their emission performance (Figure 2-1, Step 4), concluding to the recommendations of technology packages (Figure 2-1, Step 5) that will be considered in the policy options considered in the impact assessment.

As described in the Methodology (Chapter 2), Step 3 aims at identifying (within a long list) the potential future technologies that are subject to further evaluation and is based on internal data / information / knowledge / experience of the CLOVE members on the development of emission control technologies, and additional input coming from stakeholders through direct consultation or literature. After selecting the potential future technology packages, Step 4 assesses their emission performance based on total vehicle simulations using tools and software of the CLOVE members, test data provided by stakeholders from demonstrator vehicles that integrate similar technologies and additional emissions data collected during the consultations and/or retrieved from literature (including prototypes developed in the context of European research projects). The ultimate outcome of this technology analysis is the construction of meaningful technology scenarios (Step 5) and their corresponding emissions performance, along with the respective cost estimates. These scenarios have formed an input to the impact assessment study.

7.1 Assessment of potential future technologies

7.1.1 Outcomes from the analysis of the emissions database (Step 2, Chapter 4)

Based on the results from the analysis of the emissions database and taking into consideration the emission control technologies integrated in the tested vehicles[16], Euro 6d petrol vehicles that present the lowest emissions (within the current RDE boundary

[16] These are described in detail in Annex 2 of the present report.

conditions) utilise a combination of close-coupled and underfloor TWC to achieve fast warm-up and address high load operation, with a GPF which may be incorporated with one of the catalysts as a cGPF (4WC).

Diesel vehicles show a greater range of emission control configurations, although all utilise diesel oxidation catalysts (DOC) and diesel particulate filter (DPF) technologies, and active SCR with urea dosing, while ammonia slip catalysts (ASC) are now established as a standard component. These are applied in various combinations and sequences for optimum performance, with LNT (also acting as DOC) or NOx storage catalyst (NSC) used to enhance cold start NOx emissions control in some applications. At the engine side, either cooled HP EGR or HP and LP EGR systems are used to reduce engine-out NOx, with optimised combustion and fuel injection systems to minimise emissions.

These technologies ensure compliance with emission limits within the boundaries of the current RDE regulation. However, as concluded in Chapter 4, a number of issues remain, particularly when vehicles are driven outside the testing boundaries of the current RDE regulation. These issues are related to driving situations and events under which high emissions are experienced, such as:

- Cold start - short trips
- Low ambient temperature
- High engine power events/periods:
  - Harsh accelerations
  - Uphill driving, high vehicle payload, and/or trailer pulling
  - High vehicle speed
- Idling and low load driving which may occur during traffic congestion (severe stop-and-go situations)
- DPF regeneration and when filter is clean
- High SPN emissions from technologies currently not covered by the regulation (PFI and NG).

7.1.2 Identification of potential future technology packages (Step 3)

To address the remaining emission control issues, several individual technologies are considered, based on expert knowledge within CLOVE and input from stakeholders (consultation and existing literature). These technologies include:

- Close-coupled catalysts to optimise heat-up and reduce cold start effect.
- Larger emission control systems (or additional catalyst bricks), to handle the increased exhaust gas flow at high speed/load operation, by reducing space velocity and increasing residence time of the exhaust gas in the catalyst.
- For stoichiometric petrol engines: GDI engine with full map lambda-1 operation, combined with engine design and combustion optimisation. The target is to eliminate fuel enrichment in transients and in high-load operation and utilise advanced technologies for component protection (e.g., water injection).
- Particulate filter with high filtration efficiency from the clean state.
- Electrically Heated Catalyst (EHC) to address emissions related to cold start, the impact of which is magnified in short trips and in low ambient temperatures. EHC is facilitated by hybridisation (at least mild at 48V).

- Thermal management of emission control through hybrid operation – load-controlled warm-up and minimising extreme operation by utilising capabilities of full and plug-in hybrid systems. Mild hybrid systems can be used to reduce or increase the engine load with the electric motor (EM) for thermal management or to avoid high emissions in transient driving conditions like accelerations. Full- and plug-in hybrid systems also enable pure electric driving with limited range to avoid low load conditions of the engine, improve efficiency and emissions. With bigger EM power the HEV systems can also cover more transient conditions and reduce the operation area of the internal combustion engine and therefore transient emissions.

This kind of technologies are integrated on top of the considered baseline emission control systems. The latter are presented in Table 7-1. As part of the targeted consultation of expert stakeholders conducted to support the impact assessment study, respondents were asked to provide details concerning emissions control technologies for EURO 7[17] that build upon this baseline.

Table 7-1: Technology baseline for petrol and diesel cars/vans

Powertrain	Technology package
Baseline Petrol	Stoichiometric GDI + TWC + GPF
Baseline Diesel	DOC+SCRF + uf(SCR+ASC) + Twin Urea Injection(*)

(*) Twin urea injection is currently moderate in production Euro 6d vehicles, but its inclusion in demonstrator vehicles showed the best performing vehicles have adopted this technology, and stakeholder feedback suggest this is considered a baseline for development.

Stakeholders were found to strongly suggest the integration of a number of technologies in future emission control systems. A literature review also provides input on emissions control technologies that are foreseen for the future. The detailed list of the technology packages recommended in consultations and the literature is given in Table 7-2 and Table 7-3: for petrol and diesel cars/vans, respectively.

The common ground of the recommended technology packages is to achieve a significantly lower level of exhaust emissions under the current RDE testing boundaries. Only a few works and analyses actually cover the full range of current RDE testing conditions, including for example test cases with aggressive driving (characterised by high $v \times a_{pos}$ values) or focusing on particular events (e.g., cold start or DPF/GPF regeneration). Furthermore, in several studies the target is "zero-impact" on air quality. Almost all the studies exclusively address the currently regulated species, with most of them focusing on NOx and particle emissions, covering in some cases sub-23nm particles, as well. The following paragraphs give an overview of the recommended technology packages.

For petrol powertrains, the main technologies recommended in the consultations and the literature, on top of the Euro 6d baseline, are the EHC combined with a larger catalyst volume close-coupled to the engine, a particulate filter with higher filtration efficiency (FE), a GDI engine design and combustion optimisation with full map lambda-1 operation, and the optimised implementation of hybridisation (from mild 48V to full >300V systems). In some cases, additional DeNOx systems (NSC, pSCR) are integrated, while any slip of NH_3 is treated with an ASC (or CUC) supported by auxiliary air injection in the exhaust line (Hopwood & Shalders, 2020; Kapus, 2020). Without an ASC (CUC), NH_3 control would require very accurate control of lambda and oxygen storage in the TWC.

Bosch is developing a petrol demonstrator vehicle targeting CO, HC, NOx and PN emission levels below 20% of the current Euro 6 limits, during on-road operation and even under

[17] The relevant questions from the 2nd targeted consultation can be found in Annex 3 of the accompanying Annex report.

aggressive driving (Pauer et al., 2020). The vehicle integrates advanced multi-injection strategies with fuel pressures up to 500 bar, and lambda-1 operation in the entire operating range combined with water injection for component protection and advanced model-based control of catalyst O_2 content. The EATS provides increased TWC volume (cc and uf) and a GPF with FE>90% under cold start at -7°C followed by aggressive real-world driving. Particularly for cold start emissions, a burner is integrated upstream of the ufTWC, applying a strategy with 2-3s pre-heating that reduces HC, CO and NOx emissions by 45-60% in the first 200s after a cold start at -7°C. The powertrain is completed with a 48V electric machine at P0 topology used for engine load control, particularly during cold start. The combination of these technologies results in emission levels very close to the initial target, achieving 13.2 mg/km NOx, 1.26×10^{11} #/km, 120 mg/km CO and 28 mg/km HC emissions. Full integration of all the emission reduction measures and optimised calibration of the complete system is expected to enable further reductions.

Another petrol demonstrator developed by AVL, targeted the lowest possible pollutant emissions. The powertrain consists of a turbocharged GDI engine with full map lambda-1 operation and cooled exhaust manifold, assisted by a 48V 15kW electric machine at P2 topology. The emission control system includes two packages, the first being a potential EURO 7 system and the second targeting zero emission impact, as shown in Figure 7-1 (Kapus, 2020; Kapus et al., 2020). The vehicle is evaluated under a demanding schedule consisting of 8km urban driving after a cold start. Without considering any electric drive, the potential EURO 7 system with preheating results in 21% lower NOx emissions, while integration of e-drive leads to 65% reduction, compared to the Euro 6d baseline. When considering the complete zero emission impact system, then NOx reduction reaches 92% in the 8km urban trip, corresponding to 6.27 mg/km. The levels of other gaseous emissions are 21.68 mg/km HC, 3.56 mg/km CO and 0.17 mg/km NH_3.

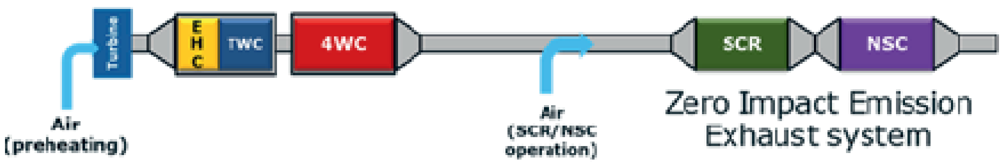


Figure 7-1: Exhaust layout of AVL petrol demonstrator (Kapus, 2020; Kapus et al., 2020)

Thermal management of the EATS after the cold start and during the warm-up phase is critical, particularly when considering short trips. Although various technologies can be implemented to control catalyst temperature (Gao et al., 2019), the electrically heated catalyst (EHC) is included in almost all the systems recommended in the literature and by stakeholders during the consultations. The EHC allows the elimination of engine measures (e.g., retarded injection/spark timing, higher idle speed, increased load) to heat-up the EATS during cold start, supporting the reduction of engine-out CO, HC and soot emissions during the warm-up phase. However, the electrical energy used in the EHC to warm-up the EATS may have a negative impact on the total fuel consumption and CO_2 emissions and needs also to be taken into consideration in the evaluation of the system.

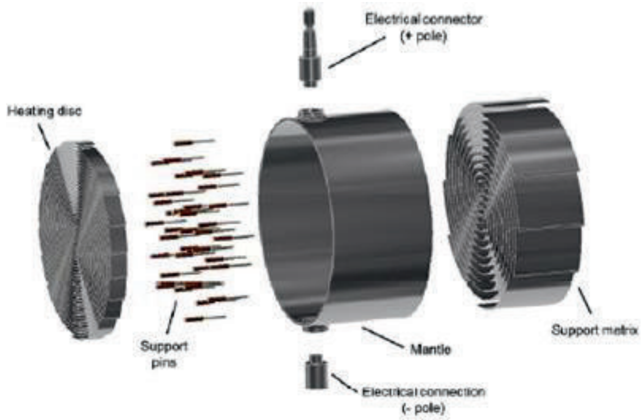


Figure 7-2: Structure of the electrically heated catalyst (Laurell et al., 2019)

An electrically heated element/disc (that can be also catalyst-coated) is integrated in the emission control canning, supported by the second part of the catalyst (support matrix), as illustrated in Figure 7-2 (Laurell et al., 2019). The EHC can be implemented with 12V systems, but the higher power of the 48V circuit enables much faster heating and reaching of light-off temperature (Jean et al., 2020). Electrical heating supports the exothermic reactions in the catalyst, further accelerating catalyst heating. The control strategy of the EHC is key to the final emission levels. Heating only after engine start delays catalyst light-off; hence preheating is an option, which, however, requires an auxiliary air injection system since there is zero exhaust flow, and this adds complexity and may saturate the TWC with oxygen during pre-heating (associated with NO_x peak after engine start). In the case of preheating, NOx and HC emissions can be reduced by 50% during the first 30s after a cold start (Laurell et al., 2019). Optimisation of the heating strategy can reduce HC emissions by 70% in the FTP75 cycle (Jean et al., 2020). In case of coated EHC elements, the durability of the coating has to be evaluated due to stronger thermal aging caused by high temperatures and high temperature gradients during heating.

Another technology to address the cold start effect, by fast catalyst heating, is the burner. A combustion chamber (in the form of a mini-burner) is mounted in front of the emission control system (offset from the main path of the exhaust gas), with its independent control system (air and fuel supply, spark plug control). This enables the activation of the burner even before the engine start (pre-heating), reducing the time until the catalyst reaches light-off by half (TENNECO, 2021). In addition, at low load operation, the burner can be activated to keep the emission control system warm. In terms of emission impact, a simulation study on a petrol vehicle indicated lower CO, HC and NOx emissions by 60%, 20% and 90%, respectively (TENNECO, 2021). As already described in the Bosch demo, HC, CO and NO_x emissions can be reduced by 45-60% in the first 200s after a cold start at -7°C, applying 2-3s pre-heating (Pauer et al., 2020 The burner can operate independently of other vehicle systems (including before engine start) and does not absorb battery energy as the EHC does. On the other hand, the pollutant emissions, as well as the extra fuel consumed, of the burner itself must be considered in the assessment of the vehicle environmental performance.

In order to achieve lower particle emission levels under all driving conditions (including those beyond the current RDE extended conditions), a GPF with high filtration efficiency (FE) from the clean state, i.e., before soot accumulation, is required. At the same time, pressure drop must be kept as low as possible, to minimise the fuel consumption penalty and associated CO_2 emissions. Modern state-of-the-art (2nd generation) GPFs with optimised material and structure (wall thickness, mean pore size) achieve FE reaching 90% with minimal impact on fuel consumption due to increased pressure drop (Yoshioka et al. 2019). PN emissions with an optimised bare GPF during a normal RDE test are 1×10^{11} and below 6×10^{10} #/km in the total trip and urban part, respectively. In an aggressive driving

RDE test, PN emissions with the optimised bare GPF remain below 2×10^{11} #/km (Yoshioka et al. 2019). Optimised catalytic GPFs can also reach high FE from the clean state, reaching FEs close to 100% with minimal soot loading. Beginning from the soot-free state, optimised cGPF achieves 83.5% FE in moderate and dynamic RDE tests, with average pressure drop from 9.9 to 13.4 mbar (Mitsouridis and Koltsakis, 2019). All these findings refer to particle size above 23nm. The requirement of high FE extends to the sub-23nm area as well, where FE is expected to be further increased due to diffusion (Samaras et al., 2020; Dorscheidt et al., 2020). This is confirmed at least in the WLTC by the PaREGEn demonstrator vehicle, where the coated GPF achieves 85.5% FE for particle size >23nm and 95.9% FE for particle size down to 10nm (Osborne et al., 2019). Further advanced developments on the so-called 3rd generation GPFs, going beyond the current Euro 6 requirements, aim at addressing elevated PN emissions under demanding operating conditions (high driving dynamics, very low temperature) when considering particles with size ≥10nm. With these advancements, it is shown that a GPF can reach FE in the range of 95-99% from the clean state, i.e., without ash or soot accumulation, with minimal impact on pressure drop (Their et al., 2020). The so-called membrane technology, initially developed for SCRF applications (Iwasaki et al., 2011; Koltsakis et al., 2012), is now considered as an alternative for GPF as well. With this kind of technology, an additional filtration layer is added on the inlet side of the wall, increasing the FE from the clean state and accelerating the soot cake formation, with limited increase of back pressure (Liu, 2020; Liu et al., 2019).

In summary, considering all the recommended technologies in the literature and the consultation, Figure 7-3 presents indicative examples of potential EURO 7 technology packages for petrol powertrains. According to the single consultation feedback covering (aggressive) RDE testing conditions, the most advanced emission control systems for petrol powertrains are reported to achieve 45 mg/km NO_x, 10 mg/km NH_3, 8 mg/km N_2O and 700 mg/km CO emissions. The possible EURO 7 technology packages suggested in consultations and literature for the petrol powertrains are summarised in Table 7-2.

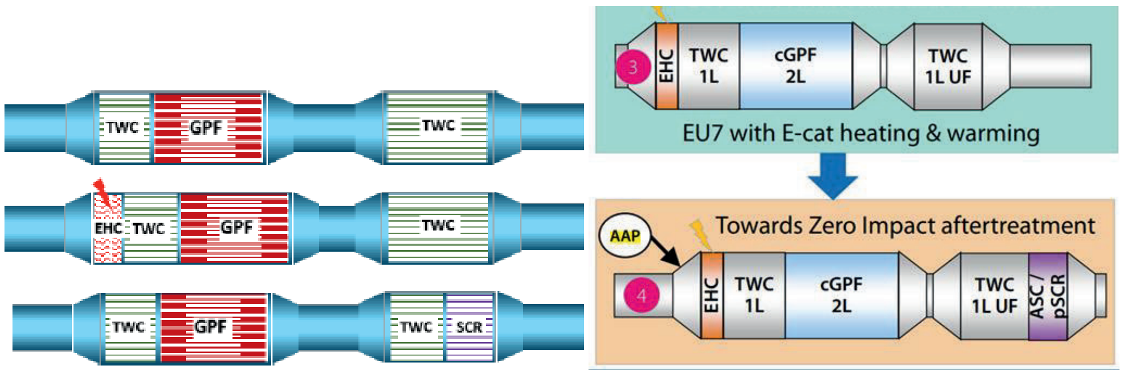


Figure 7-3: Indicative examples of potential EURO 7 exhaust emission control technologies for petrol cars and vans, as suggested in literature and consultation (Sources: Joshi 2020; Hopwood & Shalders, 2020)

Table 7-2: Overview of potential EURO 7 technology packages for petrol cars and vans recommended in consultations and literature

Petrol cars/vans			
Technology package	**Particular characteristics**	**Source**	**Reference**
cc(EHC+TWC+GPF)	• Larger TWC	OEM	Consultation

Petrol cars/vans			
Technology package	**Particular characteristics**	**Source**	**Reference**
	• EHC thermal stability issues	Association	
cc(EHC+TWC+GPF) + uf(ASC)	• Larger TWC • EHC thermal stability issues	OEM	Consultation
48V P2 + GDI + cooled EGR + cc(EHC+TWC+GPF) + uf(TWC)	• Engine load optimisation by 20kW 48V P2[1] • Accurate control of lambda and oxygen storage • GPF with ≥95% FE	Supplier	Consultation
48V P2 + GDI (pre-chamber ignition) + cc(EHC+TWC+GPF) + uf(TWC)	“Zero Impact” emission system – low electrification • Engine load optimisation & e-drive by 30kW 48V P2[1] • 10kW battery with plug-in charging • 400-600 bar petrol direct injection[a] • Pre-start catalyst light-off (pre-heating, EHC or fuel burner) [a] • Accurate control of lambda and oxygen storage • Coated GPF with ≥95% FE	Supplier	Consultation
PHEV P2 + Lean AFR (pre-chamber ginition) + cc(EHC+TWC+GPF) + uf(TWC)	“Zero Impact” emission system – high electrification • Engine load optimisation & e-drive by HV P2 plug-in system • Lean AFR & pre-chamber ignition • uf(TWC) with reduced PGM loading • Pre-start catalyst light-off (pre-heating, EHC or fuel burner) [a] • Accurate control of lambda and oxygen storage • Coated GPF with ≥95% FE	Supplier	Consultation

Petrol cars/vans			
Technology package	**Particular characteristics**	**Source**	**Reference**
GDI+EHC+TWC+GPF + preheating with air	• EHC • NOx sensor-based control	Supplier	Consultation
cc(TWC+GPF) + uf(TWC)	• Coated or bare GPF	Supplier	Consultation
cc(TWC+TWC+GPF) + uf(TWC)			
cc(TWC+cGPF) + uf(TWC)	• Larger TWC • Increased lambda-1 area	Ricardo	Hopwood & Shalders 2020
cc(TWC+cGPF) + uf(TWC+ASC/pSCR)			
cc(EHC+TWC+cGPF) + uf(TWC)			
cc(EHC+TWC+cGPF) + uf(TWC+ASC/pSCR)	• Larger TWC • Increased lambda-1 area • Zero impact aftertreatment • Auxiliary air injection		
48V P2[1] + GDI + cc(EHC+TWC+4WC) + uf(pSCR+EH-NSC)	• Zero impact configuration • 15kW 48V P2[a] (DCT gearbox) • Full map lambda-1 • Auxiliary air injection	AVL	Kapus 2020, Kapus et al. 2020
48V P0[1] + GDI + cc(TWC+GPF) + burner + uf(TWC)	• 500 bar multi-step injection • Full-map lambda-1 • Water injection for component protection • Model-based control of catalyst O_2 content2-3s preheating strategy with burner[1]	Bosch	Pauer et al. 2020
cc(TWC+GPF) + uf(TWC)	• GPF with high filtration efficiency • Coated GPF • Hydrocarbon Trap (HCT)	Corning	Joshi 2020
cc(EHC+TWC+GPF) + uf(TWC)			
cc(TWC+GPF) + uf(HCT+TWC)			
cc(TWC+GPF) + uf(TWC+pSCR)			

[a]: Px denotes the position of the electric machine (EM) in a hybrid powertrain, as follows: x=0: EM at the front-end accessory drive, x=1: EM integrated on the crankshaft (flywheel), x=2: EM at the transmission input shaft (after the clutch), x=3: EM at the transmission output shaft, x=4: EM on the axle not powered by the ICE.

After a similar review of the technology packages suggested in consultations and literature for the diesel powertrains (as summarised in Table 7-3), it is concluded that the main technologies considered (Avolio et al., 2018; Romanato et al. 2018; Joshi, 2020; Kapus, 2020), on top of the Euro 6d baseline (Table 7-1), are the EHC and further deNOx capacity with more SCR bricks, close-coupled to the engine. Mild hybridisation (with 48V systems) is also widely considered, while the twin urea injection is considered as standard to all the systems (confirming the initial inclusion of this feature to the baseline). Dual loop EGR (HP / LP) is also integrated in some of the recommended technology packages (Kapus, 2020). A configuration with pre-turbine EATS has also been recommended, combined with an electrically assisted turbocharger/compressor to compensate for reduced exhaust gas enthalpy and long routing (particularly during transients) (Lindemann et al. 2019, Netterscheid et al. 2020).

A particular issue for diesel vehicles is N_2O, which is a potent greenhouse gas and can also cause health problems at high concentrations. N_2O is formed in the exhaust emission control system of diesel vehicles, primarily in the SCR and secondly during the oxidation processes in DOC, LNT or ASC. Starting from the latter case, NH_3 oxidation in the ASC (in the presence of NO, as well) and NO reaction with HC (in lean mode) and H_2/CO/HC (in rich mode) in the LNT, all result in N_2O formation. Since N_2O is a side product, it can be controlled mainly by changing the conditions (e.g., temperature window) of these oxidation processes or the specifications of the relevant components (e.g., PGM loading in the DOC), impacting negatively, though, the overall performance of the emission control components. In the SCR, which has the highest contribution to N_2O formation, the reaction of NH_3 with NO_2 or with NO (in the presence of O_2) produce N_2O. NH_3 oxidation in the SCR at high temperatures also produces N_2O. The type of the SCR plays an important role in the formation of N_2O, with vanadium-based SCR (V-SCR) systems being preferable. However, V-SCR cannot withstand high temperatures (>550 °C) and, thus, cannot be considered possible solutions for light-duty vehicles. Unless new catalyst technologies are developed in the future, appropriate adaptation of existing emission control systems together with suitable calibration (balancing the control of CO, HC, NOx and NH_3 emissions with N_2O formation) can be implemented for N_2O control.

Considering the above-mentioned technology packages in the literature and the consultation, Figure 7-4 presents indicative examples of potential EURO 7 technology packages for diesel powertrains.

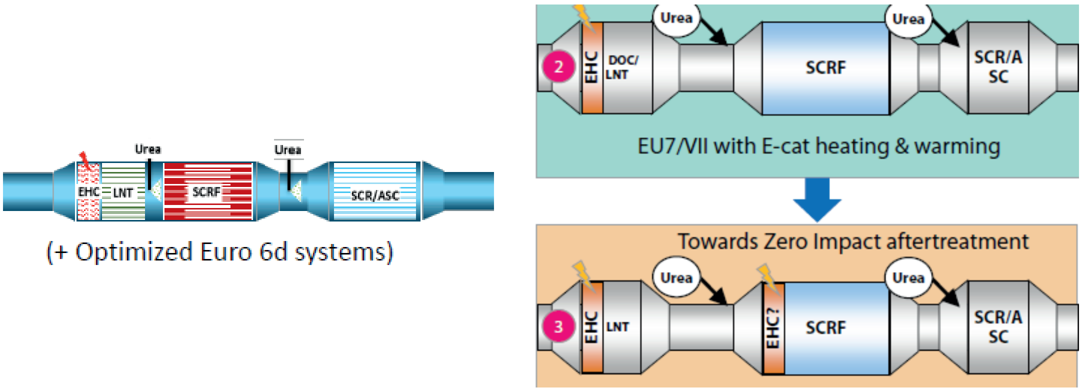


Figure 7-4: Indicative examples of potential EURO 7 exhaust emission control technologies for diesel cars and vans (Sources: Joshi 2020; Hopwood & Shalders, 2020)

Table 7-3: Overview of potential EURO 7 technology packages for diesel cars and vans recommended in consultations and literature

Diesel cars/vans			
Technology package	**Characteristics**	**Source**	**Reference**
cc(NSC+SCRF+SCR) + uf(SCR/ASC)	• Twin urea injection	OEM	Consultation
cc(DOC+SCR+SCRF+SCR) + uf(SCR/ASC)	• Particularly for vans • Twin urea injection	OEM	Consultation
LNT+SCRF+SCR+ASC	• Twin urea injection	Supplier	Consultation
48V P0[1] + DOC+SCRF+SCR+ASC	• Twin urea injection • Slight CO_2 benefit in WLTC	Supplier	Consultation
48V P2[1] + DOC+SCRF+SCR+ASC	• Twin urea injection • Big CO_2 benefit in WLTC	Supplier	Consultation
EHC[1]+DOC+SCRF+SCR+ASC	• EHC[a] • Twin urea injection	Supplier	Consultation
48V P0[1] + cc(LNT+SCR+SDPF) + uf(SCR+ASC)	• Twin urea injection • HP / LP EGR	AECC	Consultation, Demuynck et al. 2019
cc(EHC+LNT+SCR+SCRF) + uf(SCR+ASC)	• EHC • Twin urea injection • Optimisation of thermal management • Increased SCR volume	Supplier	Consultation

Diesel cars/vans			
Technology package	**Characteristics**	**Source**	**Reference**
48V P0[1] + cc(EHC+DOC+SCR+SCRF) + uf(SCR+ASC)	• 12kW 48V P0[a] • 4kW 48V EHC • Twin urea injection • Big CO_2 benefit in WLTC	Continental	Avolio et al. 2018
cc(EHC+DOC/LNT) + uf(SCRF+SCR/ASC)	• Twin urea injection	Ricardo	Hopwood & Shalders 2020
cc(EHC+LNT) + uf(EHC+SCRF+SCR/ASC)			
48V P2[1] + cc(EHC+LNT+SDPF) + uf(SCR+SCR/ASC)	• Zero impact configuration • 30kW 48V P2 (DCT gearbox) • HP / LP EGR • Twin urea injection	AVL	Kapus 2020
cc(EHC+LNT+SCRF) + uf(SCR/ASC)	• EHC • Twin urea injection	Corning	Joshi 2020

[a]: Px denotes the position of the electric machine (EM) in a hybrid powertrain, as follows: x=0: EM at the front-end accessory drive, x=1: EM integrated on the crankshaft (flywheel), x=2: EM at the transmission input shaft (after the clutch), x=3: EM at the transmission output shaft, x=4: EM on the axle not powered by the ICE.

Taking into consideration all the above, comprehensive emission control packages were developed with a number of potential future technologies separately for petrol (potentially applicable also to CNG and LPG vehicles) and for diesel cars and vans. These technology packages are presented in Table 7-5 and Table 7-6 for petrol cars and Table 7-7 for diesel cars/vans.

The rationale followed in the construction of those Tables is:

- First the baseline technology was selected – this was largely decided on the basis of the best performing Euro 6d vehicles identified in the previous steps and which was including all the state-of-the-art EATS (shown in Table 7-1).
  - The petrol car is a mid-size sedan with a turbocharged 2.0l GDI engine equipped with a close-coupled1.8 l TWC and an underfloor 1.2 l uncoated GPF and a specific engine power of 67 kW/l displacement.
  - The diesel car is a heavy SUV with a turbocharged 2.0l engine equipped with cooled HP-EGR and LP EGR, a close-coupled1.8 l DOC and SCR and an underfloor 3.0 l SCRF with twin urea injection
- Both diesel and petrol technologies are split into two main sub-categories
  - Conventional including mild hybrids (mHEVs), i.e. 48V technology of P0 topology (see Table 7-5 for petrol and Table 7-7 upper half for diesel)

  - Plug-in hybrids (including HEVs) of P0/P2 topology i.e. technologies capable of pure electric propulsion, see Table 7-6 for petrol and Table 7-7 lower half for diesel)

- The above split indicates the expectation that in the 2025 to 2030 timeframe all internal combustion engine cars will be at least mild hybrids, a trend exclusively imposed by the CO_2 emissions regulations.

- Additional measures were added sequentially on the baseline technologies, to simulate more advanced emission control technologies at each subsequent step. Hence:
  - The technology packages G2 to G7 in Table 7-5 for petrol mHEVs include first an update of the combustion system to stoichiometric operation in the whole engine map. This is assumed to be realised with a cooled exhaust manifold, high charge motion design of the combustion, and a 350-bar centrally mounted multi hole injector. Additionally, the calibration of the ICE is optimised especially in catalyst heating and warm up. The Lambda control during catalyst heating is optimised for low raw emission with open loop control during the first 15s and then closed loop control of the relative AFR to stochiometric operation. Whole map stoichiometric operation enables emission conversion in the TWC at all operating condition. The higher mass flow with stoichiometric operation leads to high space velocity in the catalyst and therefore an approx. doubling of the volumes of the catalyst (2.2 l TWC and 1.6 l GPF) and improvement of GPF filtration efficiency (G2) is needed. Then a simple mild-hybridisation of the base engine is added in G3 (8/15 kW cont./peak BSG, 1.2kWh Li-Ion battery) using an advanced combustion engine start with the 48V belt starter generator. Similarly, a hybridisation of the G2 package (G4) is used. In the G5 package a 4kW EHC is added to the G4 configuration without preheating (EHC start heating at combustion engine start and electric power for the EHC is provided by the ICE via the BSG). 10s preheating with secondary air and an ammonia catalyst is added at the G6 step which is finally followed in G7 by an exchange of the EHC with 15kW burner equipped with a 10s preheating capability.
  - The technology packages G8 to G13 in Table 7-6 for petrol PHEVs follow a similar sequence of steps as in the case of mild hybrids; at first it should be stressed that the base IC engine of the PHEV is similar as in the case of mHEVs but with downsizing to 1.5l 3 cylinder with reduced power of 105 kW, operated evidently differently by the controller to take advantage of the full hybridisation. Also, the catalyst and GPF used are similar as in the relevant cases of the mHEVs. The volumes of the catalysts are adapted to the lower engine power of the PHEV engine. Further differences are the longer duration capability of the preheating (90s) underpinned by the higher capacity batteries of the PHEV in G11 and G13, the larger (8kW) power of the EHC in G13 and the addition of a passive SCR and an LNT in G13. To keep the comparison in the heating on an equal basis, the burner is able to operate for 30s (instead of 10s in the mHEVs case)
  - The technology packages D1 to D3 for diesel mHEVs include at the first D1 step mild hybridisation, advanced engine heating calibration (for catalyst fast heat-up) and a larger number of EATs that include a close coupled 1.0l LNT, 1.0l SCR and 4.0l SDPF followed by an underfloor 5.0l SCR and ASC. In D2 a 4kW EHC is added w/o preheating capability, a functionality added in the D3 package with 10s preheating and secondary air.
  - Finally, the technology package D4 for diesel PHEVs in Table 7-7 is basically the same as D1 with advanced hybridisation while D5 includes on top to D4 an EHC w/o preheating as well as turbine bypass capability.

Evidently these technologies are neither at the same TRL from today's perspective nor adequate for all vehicle segments. Generally higher TRLs are associated with the first technology package steps (i.e., G1 to G3 and D1), while lower TRLs are related with the higher and more sophisticated emission control steps. Also, concerns have been expressed by several stakeholders as regards the availability of higher filtration GPFs (which have typically been called Generation 3 filters), while concerns have been raised about the durability of specific components such as EHC, in view of the likely higher EURO 7 durability requirements. Moreover, due to their cost, not all technologies are adequate for all car segments. A clear example is the usage of burners which seems to be limited to larger more expensive cars (typically with higher power capabilities). Table 7-4 presents the estimated TRLs for various technologies considered in EURO 7.

Table 7-4: Estimated TRL for various technologies considered in EURO 7

Technology / Component	Estimated TRL	Comment
Hybrid systems of various topologies	9	Systems already in the market
Larger emission control devices with optimised thermal management	8	Technology exists, implementation is pending final adjustments (e.g., re-calibration) according to real operating conditions and new emission limits
Full map λ- 1GDI engine with combustion optimisation and advanced component protection techniques (e.g., water injection)	6	Technology tested on demo vehicle under real driving conditions
Advanced injection system for GDI (multi-step high-pressure injection)	6	Technology tested on demo vehicle under real driving conditions
3rd generation GPF with high filtration efficiency	5	On-road tests performed
EHC	8	System deployed already in the past. Implementation is pending adjustments (e.g., calibration, heating power/time) according to real operating conditions and new emission limits
EHC with preheating functionality and secondary air injection	6	Technology tested on demo vehicle under real driving conditions
Burner	6	Technology tested on demo vehicle under real driving conditions
CUC for petrol vehicles	5	Operation strategy still under investigation, combined with advanced lambda control
Passive SCR for petrol vehicles	6	Demonstrated in the context of Zero Impact Emission concept
LNT for petrol vehicles	6	Demonstrated in the context of Zero Impact Emission concept

Table 7-5 EURO 7 technology packages – petrol mild hybrid electric vehicles

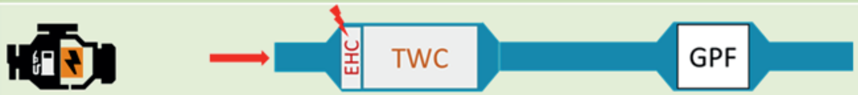
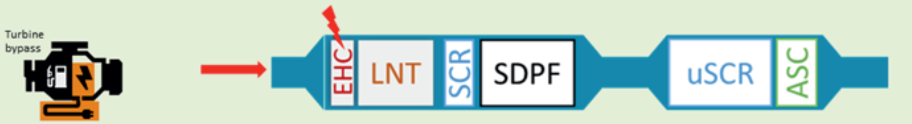
Gasoline		
Short name	Technologies/components integrated	
G1 – Base Euro 6	Base TWC, base GPF	
G2 – Base Euro 7 opt	Advanced calibration, larger TWC, improved GPF	
G3 – MHEV Base Euro 6	Mild hybrid, base TWC, base GPF	
G4 – MHEV Euro 7 opt	Mild hybrid, advanced calibration, larger TWC, improved GPF	
G5 – MHEV Euro 7 opt e-cat	Mild hybrid, advanced calibration, larger TWC, improved GPF, 4kW EHC	
G6 – MHEV Euro 7 opt e-cat 10s	Mild hybrid, advanced calibration, larger TWC, improved GPF, 4kW EHC, 10s preheating, secondary air injection, CUC (NH_3 catalyst)	
G7 – MHEV Euro 7 opt burner 10s	Mild hybrid, advanced calibration, larger TWC, improved GPF, 15kW fuel burner, 10s preheating, secondary air injection, CUC (NH_3 catalyst)	

Table 7-6 EURO 7 technology packages – petrol plug-in hybrid electric vehicles

Gasoline		
Short name	Technologies/components integrated	
G8 – PHEV Base Euro 6	Plugin hybrid, base TWC, base GPF	
G9 – PHEV Euro 7 opt	Plugin hybrid, advanced calibration, larger TWC, improved GPF	
G10 – PHEV Euro 7 opt e-cat	Plugin hybrid, advanced calibration, larger TWC, improved GPF, 4kW EHC	
G11 – PHEV Euro 7 opt e-cat 60s	Plugin hybrid, advanced calibration, larger TWC, improved GPF, 4kW EHC, 60s preheating, secondary air injection, CUC (NH_3 catalyst)	
G12 – PHEV Euro 7 opt burner 30s	Plugin hybrid, advanced calibration, larger TWC, improved GPF, 15kW fuel burner, 30s preheating, secondary air injection, CUC (NH_3 catalyst)	
G13 – PHEV Euro 7 opt e-cat 60s 8kW	Plugin hybrid, advanced calibration, larger TWC, improved GPF, 8kW EHC, 60s preheating, secondary air injection, CUC (NH_3 catalyst), passive SCR, LNT	

Table 7-7 EURO 7 technology packages – diesel mild and plug-in hybrid electric vehicles

Diesel		
Short name	Technologies integrated	
D1 – MHEV P0 Euro 7 opt	Mild hybrid, advanced heating calibration, larger EATS	
D2 – MHEV P0 Euro 7 opt e-cat	Mild hybrid, advanced heating calibration, larger EATS, EHC	
D3 – MHEV P0 Euro 7 opt e-cat preheating	Mild hybrid, advanced heating calibration, larger EATS, EHC, preheating, secondary air injection	
D4 – PHEV P2 Euro 7 opt	Plugin hybrid, advanced heating calibration, larger EATS	
D5 – PHEV P2 Euro 7 opt e-cat	Plugin hybrid, advanced heating calibration, larger EATS, EHC, turbine bypass	

7.1.3 Emissions reduction potential of future technology packages (Step 4)

After the definition of the potential future technology packages following the procedure described above, their emission reduction potential was evaluated, using:

1. Simulations of the emission performance of technology packages, using tools and software available within the CLOVE partners. A description of the simulation models used for this work is presented in Annex 2, section 2.1.2.
2. Emissions data collected during the consultations and retrieved from literature, including prototypes developed in European research projects.
3. Test data from demonstrator vehicles integrating future technology packages, provided by stakeholders.

The assessment presented and discussed below is primarily based on simulation results. The models were first validated / verified using the baseline vehicles tested at JRC and then they were used to extrapolate to the future technology steps shown in Table 7-5 through Table 7-7. The models employed were the FEV suite of models that comprise vehicle, engine and EATS simulation; the suite is a hybrid set of models including ECU models (largely look-up tables) and physical models (in particular for certain types of EATS such as SCR). The results of the exhaust emission control simulations of the FEV suite were in a few cases cross-checked and compared to Exothermia Suite results, i.e., a full physico-chemical model suite for detailed exhaust emission control simulation. Exothermia Suite results were also used to augment a few cases such as GPF and SCRF filtration with additional more in-depth analysis and extrapolations.

The evaluation of the emission reduction potential of the technology packages focused particularly on driving conditions characterised by emissions excursions, such as:

- Cold start – short trips
- Low ambient temperature
- High engine power events/periods:
  - Harsh accelerations
  - Uphill driving, high vehicle payload and/or trailer pulling
  - High vehicle speed
- Idling and low load driving which may occur during traffic congestion (severe stop-and-go situations).
- DPF regeneration and when filter is clean
- High SPN from technologies currently not included in regulation (PFI and NG)

The next paragraphs present first the test cycles that were considered representative of normal and extended conditions of use (section 7.2) and then the emission performance of the potential EURO 7 technology packages (section 7.3).

7.2 Test cycles as approximation of normal and extended conditions

The first step in the evaluation of EURO 7 technologies was the selection of representative driving cycles and test conditions that could be considered with certainty as good proxies for normal and extended conditions. To this aim, several test cycles and configurations were tested at the JRC in a dedicated test campaign (on climatic chassis dynamometer) on three latest-technology state of the art vehicles, one diesel, one petrol (GDI) conventional and one petrol (GDI) PHEV. These tests are presented in detail in Annex 2, while a short description of the main findings is included in Chapter 4 of this report. In summary, the test protocol comprised different test cycles covering a wide range of driving dynamics (from low-speed moderate driving to aggressive driving with harsh accelerations and decelerations), trip composition (tests with various combinations of urban, rural and motorway driving), ambient temperature (from -30ºC to +50ºC), as well as tests including/simulating uphill driving and driving with trailer towing. Among this long list of tests, two were selected as good approximations of normal and extended driving conditions.

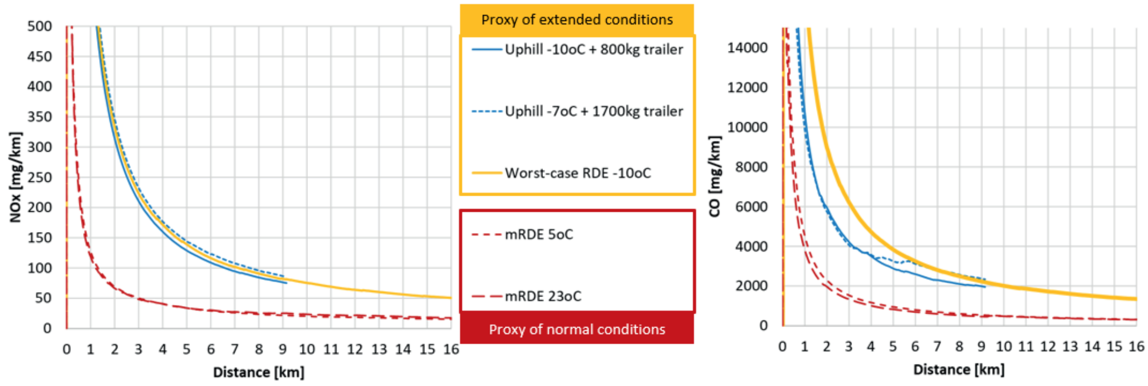
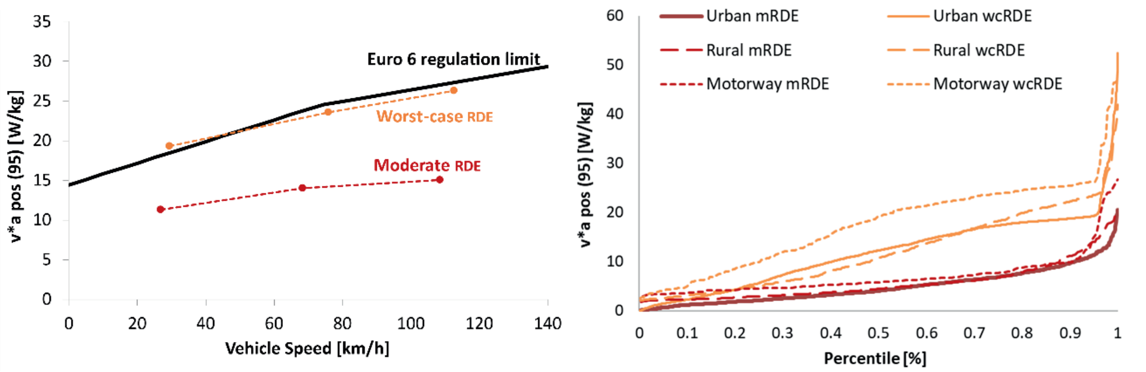


Figure 7-5: Approximation/proxy of normal and extended conditions of use based on JRC testing on a petrol Euro 6d-temp low-emission vehicle.



Test cycle	Power metric [%]
mRDE	2.9
wcRDE	39

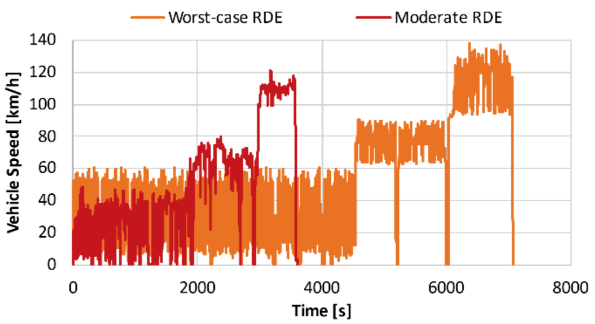


Figure 7-6: Driving dynamics characteristics in terms of v*a[95th] and power metric (first 2 km), and vehicle speed profiles for the moderate and worst-case RDE.

Figure 7-5 presents the NOx and CO emission performance of the above-mentioned petrol conventional vehicle over five representative tests. A moderate RDE test was selected as a good approximation of the normal conditions of use. This test, which is also presented in Figure 7-6, is a short version of an RDE compliant test in terms of driving dynamics, trip characteristics etc. The only parameter that does not comply with the regulation prescription is the total length which is around 50 km. This is not a critical issue for this evaluation as in EURO 7 much shorter tests will still be compliant with the regulation. Two versions of this test in terms of ambient temperature are presented here, at 23ºC and +5ºC, with the difference among those in emission levels being negligible. As regards the extended conditions of use, these can be approximated by the worst-case Euro 6 RDE test at -10oC run with 90% of the payload of the vehicle. As shown in Figure 7-5, the emission performance over this test is close to the uphill diving tests which are a combination of different worst-case conditions i.e. high engine load due to uphill driving and trailer pulling (up to 90% of max allowed by the OEM) and low ambient temperature, down to -10oC. As shown in Figure 7-6, the worst-case RDE test cycle is characterised by consecutive and sharp acceleration and deceleration events, which results in v*a[95th] values close to current Euro 6 regulation limits in urban, rural and motorway sections. The power metric for the first 2 km, as described in the testing conditions presented in Chapter 6, is also much higher than the recommended boundary for normal conditions, reaching 39%. Finally, it should be noted that the worst-case Euro 6 RDE cycle does not depict realistic driving behaviour that is possible on the public road mainly due to the extreme acceleration and deceleration events. Thus, this cycle should not be and is not taken as the basis for EURO 7 extended conditions of use, but simply as a worst-case.

7.3 Emissions performance of prospective EURO 7 technologies

Figure 7-7 to Figure 7-10 present the NOx, CO, HC and SPN emissions performance (simulation data) of selected petrol and diesel EURO 7 technologies as presented in Table 7-5 to Table 7-7. Results are provided over the moderate RDE tests at 23ºC and the Euro 6 worst-case RDE at -10ºC, which, as described in the previous section, are considered as approximations of normal and extended conditions respectively. These results are used as a basis for the determination of the recommended EURO 7 limits. The approach followed for the determination of recommendations for limit values is presented in the next section, where the functional form of the recommended limits is analysed.

It is important to note here that, as in the case of the measurement data in Chapter 4, PN emission simulation data refer to SPN_{23}, because the simulation models were calibrated based on the SPN_{23} measurement data. As further explained in section 7.5, the recommended EURO 7 emission limits refer to SPN_{10}, for which an SPN_{10}/SPN_{23} ratio was considered (based on current state-of-the-art technologies performance and engineering assessment for the expected EURO 7 technologies).

The graphs presented below provide an insight on the comparison between Euro 6 and EURO 7 technologies, the effect of different EURO 7 technologies on emission performance, the contribution of cold start in each case, as well as the potential functional form of EURO 7 emission limits. Looking comparatively at Figure 7-7 and Figure 7-8 a NO_x – CO trade-off in the petrol engines is revealed: it is deduced from both the measurements of the data base as well as the performance of the Euro 6d baseline car that the primary focus in Euro 6 RDE was on NO_x control with somewhat less attention to the CO emissions. Hence, a significant improvement of CO emission performance can be expected and achieved in EURO 7 compared to Euro 6, mainly in the case of PHEVs. This does not mean that NOx performance is not optimised in EURO 7, but CO control (mainly through accurate lambda=1 control) is expected to be favoured in the NO_x-CO trade-off.

What the analysis of the simulation data also shows is the significant cold start contribution in most pollutants and test cycles, especially in the case of the worst-case RDE which is a demanding cycle from its start. The installation of an EHC, especially when combined with pre-heating (before engine start) brings significant reduction to the cold start effect and, consequently, to cycle-average emissions. This effect is amplified in the case of the PHEVs with a 60s pre-heating phase. Additional simulations with an empty battery at the beginning of the cycle (technology package G11 – empty battery in the Figures), however, indicate that this emissions gain is much lower if the battery state of charge of the hybrid system is not adequate. As more or less expected, in this case all possible gains of the G11 technology are largely consumed by the increased cold start emissions at the beginning of the cycle induced by the necessary operation of the ICE to charge the battery. It is also of interest to discuss the differing operation of the petrol mHEVs and PHEVs with the example of NOx emissions (Figure 7-7) the PHEVs are associated with a continuous gradual increase of the emissions over time as opposed to almost stabilised emissions of the mHEVs post the cold start period. This is largely attributed to the higher overall temperature levels and hence higher overall catalyst conversion efficiencies in the exhaust of the more conventional engines; in contrast PHEVs with the intermittent operation of the ICE are generally characterised by lower overall temperature levels and hence slightly lower conversion efficiencies. This behaviour is comparable to the diesel; nevertheless, it should always be borne in mind that these are simulation results and reflect an assumed powertrain control which may be substantially different in the future EURO 7 compliant applications.

Figure 7-11 provides an overview of the simulation results of the NOx, CO and HC emission levels that can be achieved by all petrol technologies examined over the Euro 6 worst-case RDE cycle at -10ºC. Indicative results at 10 and 16 km are shown. The Figure shows again what was discussed above: Most of the (important) reduction potential of CO and HC can be harvested already with the first technology package with small overall gains thereafter. Still NOx remains the most difficult pollutant to control, with only gradual reduction with the progressive application of more effective technology packages.

The above set of emissions performance data from a variety of emissions control technologies of varying sophistication, technology readiness level and costs should be used as the basis for the construction of a meaningful set of emission limit scenarios. To do this it is necessary to also account, to a certain degree at this stage, for the expectations of vehicle fleet evolution in the future for different fuels (petrol versus diesel versus gaseous fuels), for different technologies (i.e., ICE-only, mHEVs, PHEVs) and their combinations. As scenario setting and even more so emission limit setting is not an exact science, the higher the granularity the better. Therefore, in theory, one could set up as many scenarios as the available imagined technology and fuel combinations. However, on one hand the Terms of Reference of our work, which ask for a limited number of scenarios fuel and technology agnostic, and on the other hand the available resources, which do not allow us to handle a large number of scenarios, inevitably ask for a limited number of scenarios. These scenarios should provide the necessary granularity in the analysis at an acceptable effort, while addressing the terms of reference.

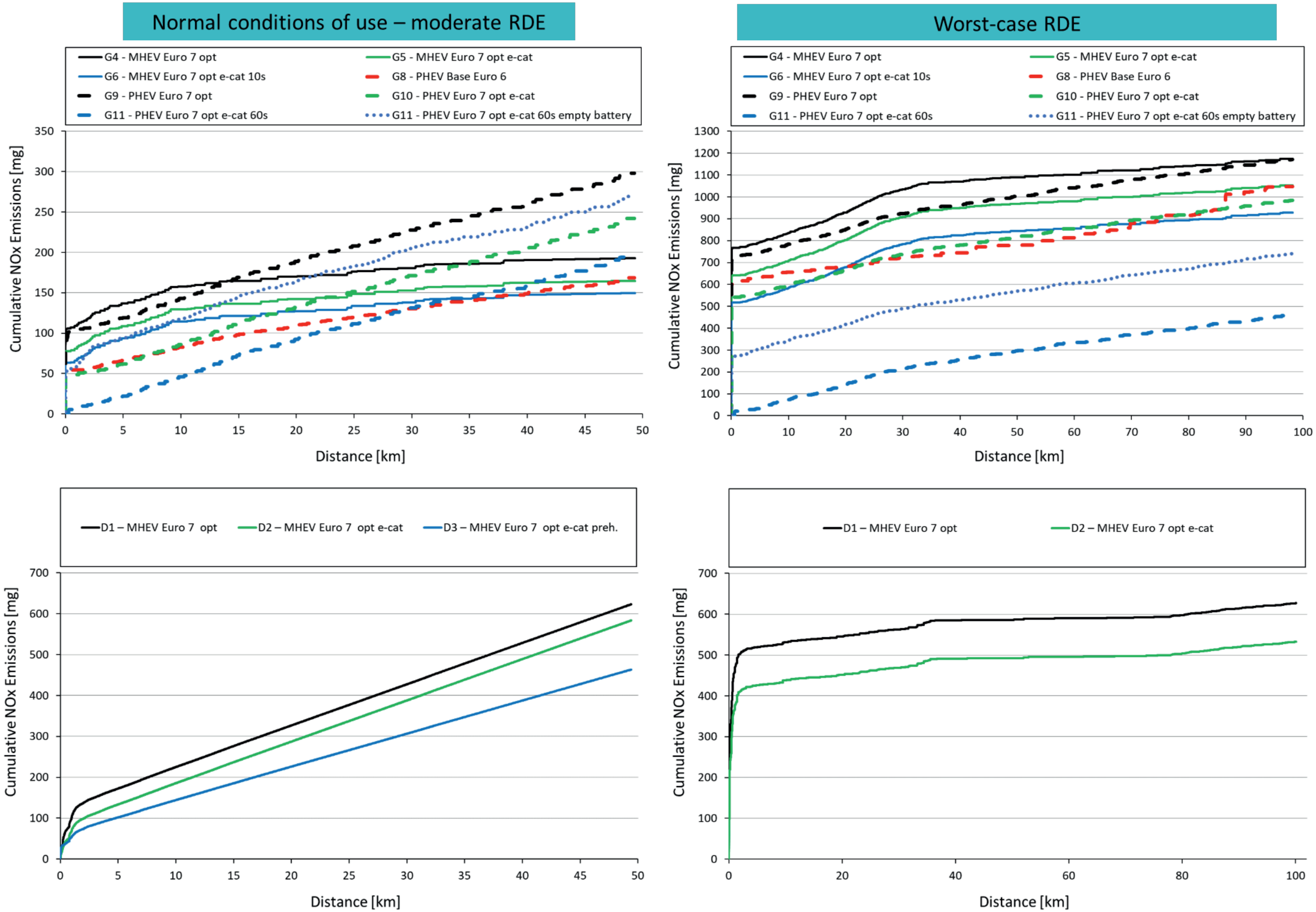


Figure 7-7: NOx emission performance (simulation data) of indicative EURO 7 petrol (upper panel) and diesel (lower panel) technologies under moderate RDE at 23ºC (left panel) and worst-case RDE at -10ºC (right panel) – solid lines refer to mHEVs; broken and dotted lines to PHEVs

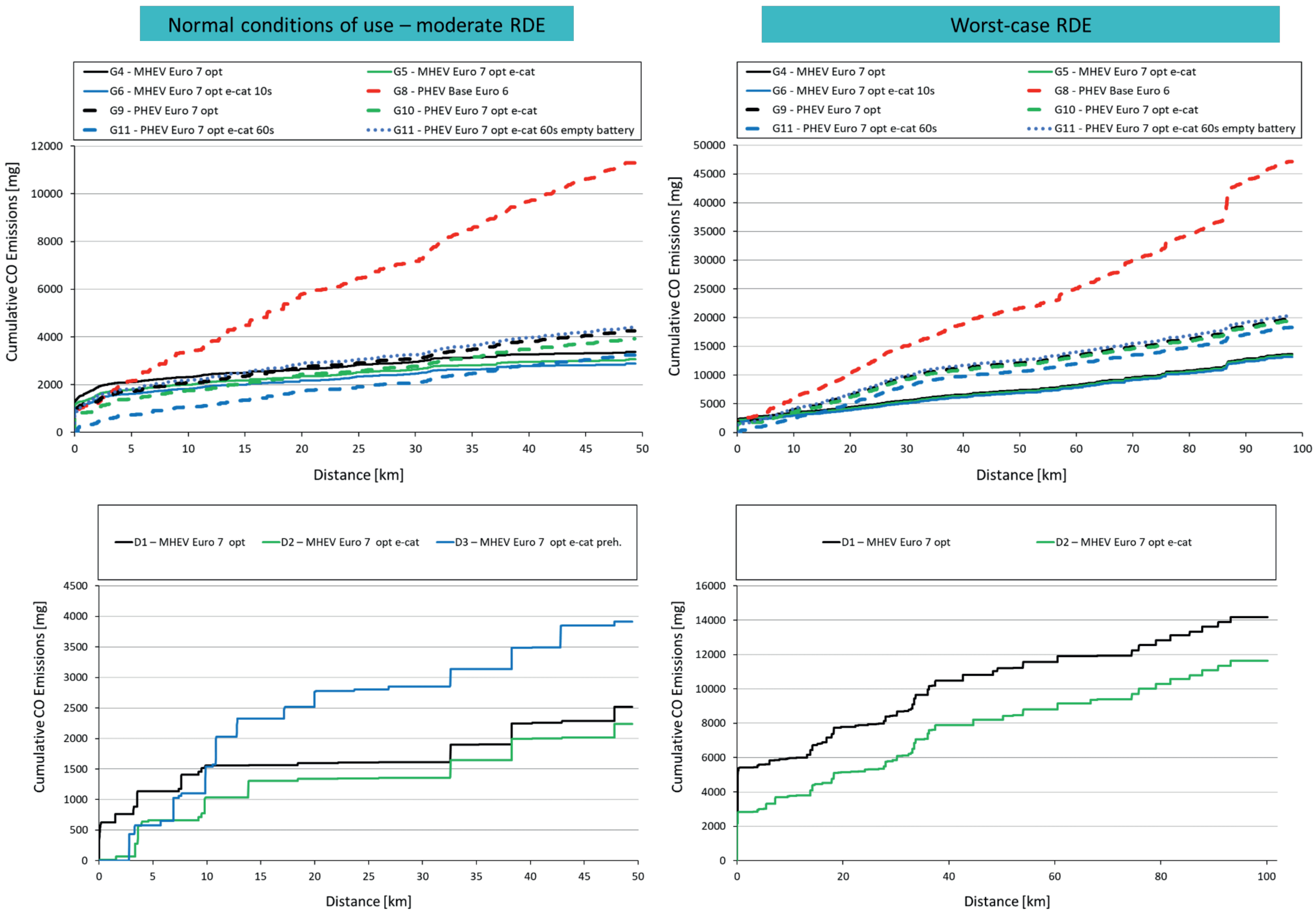


Figure 7-8: CO emission performance (simulation data) of indicative EURO 7 petrol (upper panel) and diesel (lower panel) technologies under moderate RDE at 23ºC (left panel) and worst-case RDE at -10ºC (right panel) – solid lines refer to mHEVs; broken and dotted lines to PHEVs

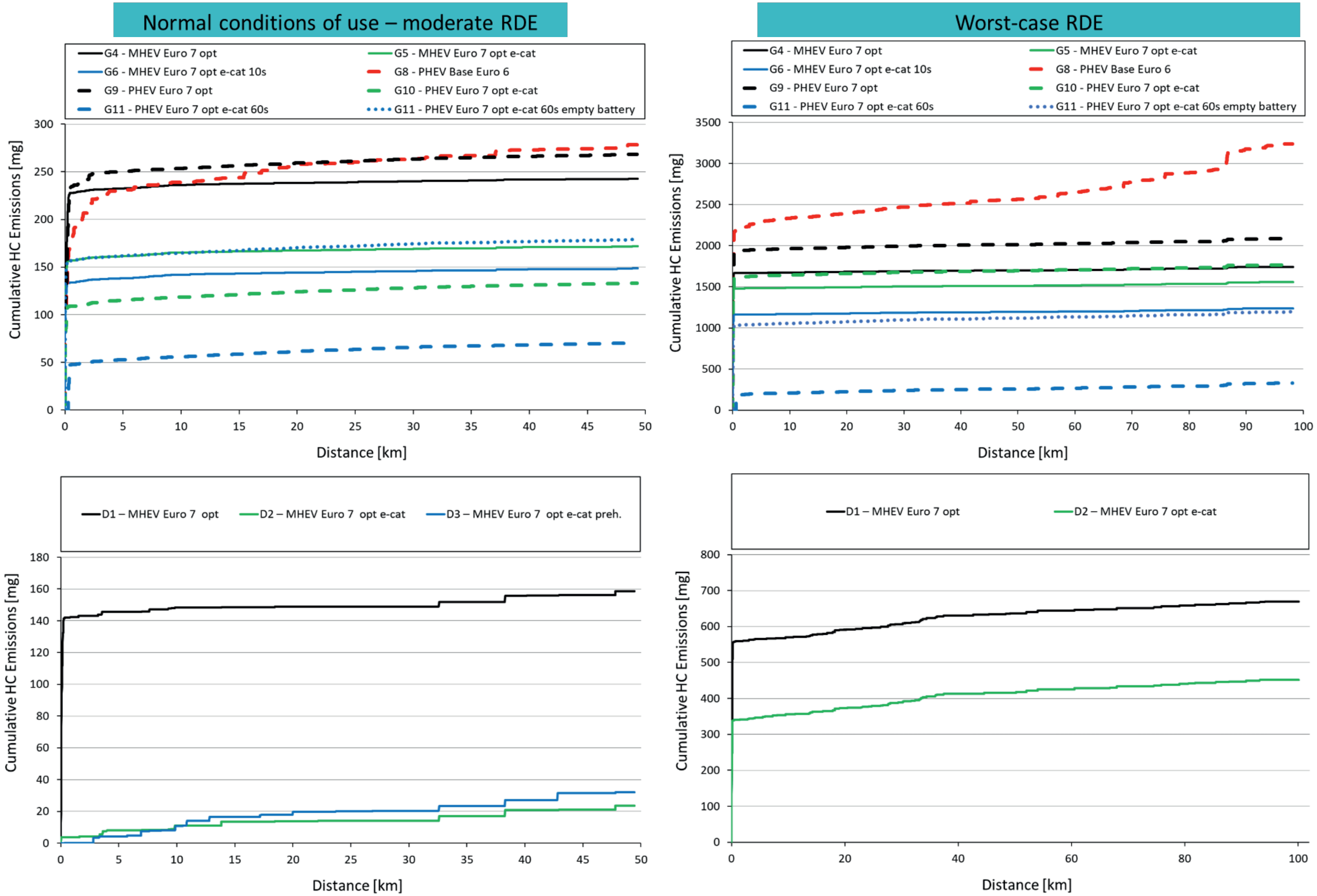


Figure 7-9: HC emission performance (simulation data) of indicative EURO 7 petrol (upper panel) and diesel (lower panel) technologies under moderate RDE at 23ºC (left panel) and worst-case RDE at -10ºC (right panel) – solid lines refer to mHEVs; broken and dotted lines to PHEVs

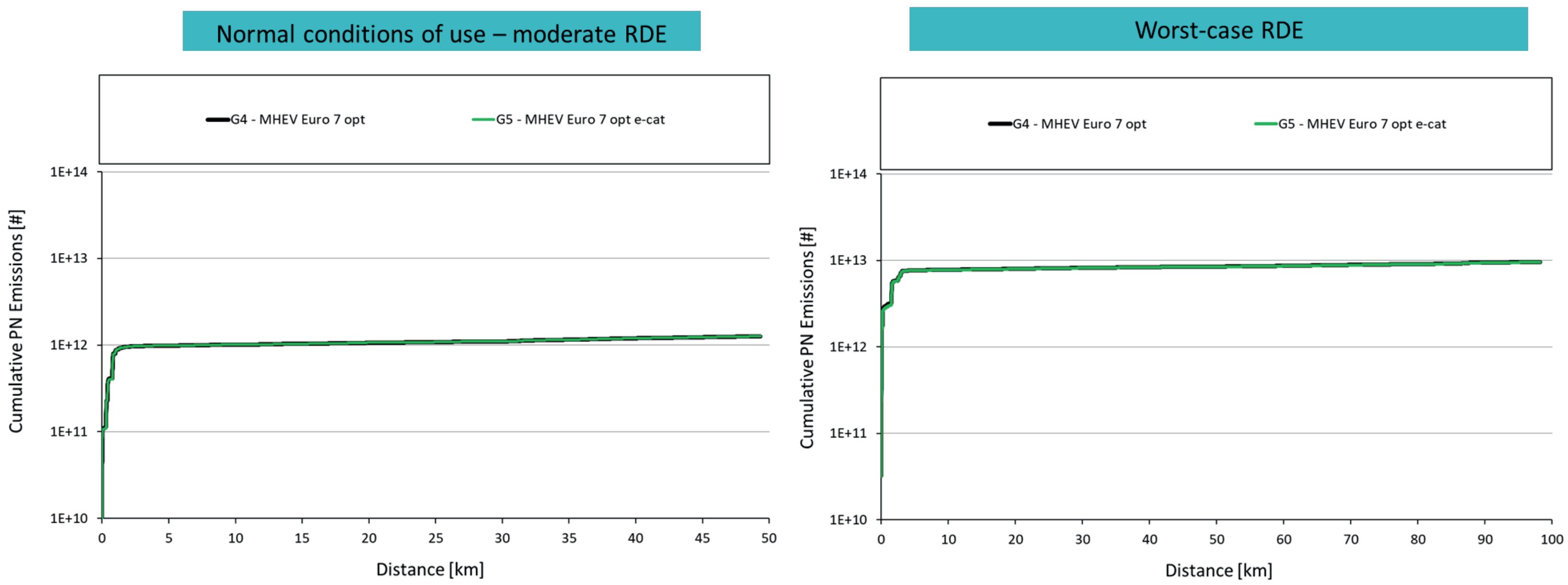


Figure 7-10: PN (SPN_{23}) emission performance (simulation data) of indicative EURO 7 petrol technologies under moderate RDE at 23ºC (left panel) and worst-case RDE at -10ºC (right panel). Note: no simulation data available for diesel.

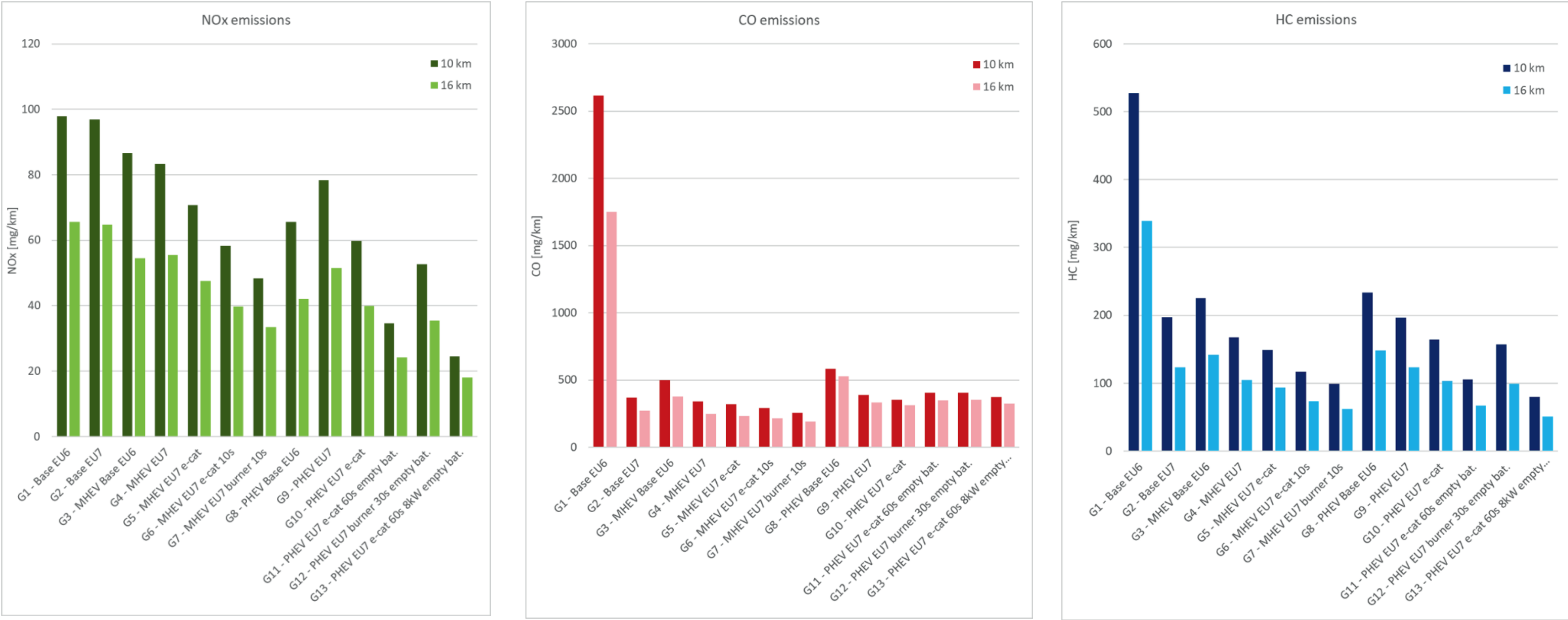


Figure 7-11: Average NOx, CO and HC emissions in mg/km of petrol technology packages at 10 and 16 km from the beginning of the Euro 6 worst-case RDE cycle at -10ºC

At this point it should be noted that according to the ToR of this study, the following Policy Options (PO) are considered:

- Option 0: Baseline scenario – No legislative change (“Euro 6/VI”) – **same limits as today.**
- Option 1: Narrow revision of vehicle emission standard (“Narrow EURO 7”) – **same limits as today.**
- Option 2: Wider revision of vehicle emission standards (“Wider EURO 7”) – **lower limits.**
- Option 3: Profound revision of vehicle emission standards (“Comprehensive EURO 7”) – **lower limits.**

In this context, it is clear that the task of the current chapter is to provide the necessary input to PO2 with respect to LDVs exhaust emissions (Chapter 11 provides input for PO3).

Taking into account the following assumptions:

- the data from the assessment of current and future technologies,
- that the ICE in an mHEV format will continue existing in the horizon of our analysis, most importantly in the smaller vehicle segments
- that PHEVs are expected to play a dominant role in the medium, MPV and SUV segments, particularly in the petrol vehicle market and much less so in the diesel market

it was considered appropriate to propose two Scenarios as input to Policy Option 2, with the following characteristics:

Scenario 1 (Balanced): All conventional ICE-only technologies are transformed to mHEVs at minimum. For petrol technology packages G4 and G5 and for diesel technology packages D2 and D3 are considered as the main technologies to comply with the emission limits of this scenario. In parallel it is considered that PHEVs will also adapt and slightly improve in terms of emissions.

Scenario 2 (Ambitious): In this scenario at least the technology packages G5 (possibly G6) and D3 will be necessary for compliance. However, it is highly likely that the technology package of choice for the OEMs will be PHEV related and hence Scenario 2 may be related with a large penetration of PHEVs of all technology packages. This could even be related with the appearance in large numbers of diesel PHEVs, which are not accounted for in our estimates below.

7.4 Functional form of emission limits

Following the analysis presented in the previous chapters, it is important to recognise the challenges of short trips (high effect of cold start), idle and stop-go traffic on a per km basis. Considering that any trip distance will be valid in EURO 7, CLOVE proposes the introduction of a two-area form of limit, as shown in Figure 7-12. A constant limit value in mg (or particles for PN emissions), referred to as “budget”, is applied up to a reference distance (set at 16 km in this case as explained in the following paragraphs), while a constant limit in mg/km (or p/km for PN emissions) is applied for trips above the reference distance. For any trip above 16 km to be compliant, the requirement is that both the budget at 16 km and the mg/km limit after 16 km are adhered to.

Figure 7-12 presents an example for the case of Scenario 1[18] and for NOx emissions at normal conditions. The trade-off and interrelation between budget and constant limit is clearly observed: the introduction of the “budget” limit allows the introduction of a low emission limit in terms of mg/km (in this case 50% lower than the lowest current limit without conformity factor), while at the same time an allowance for cold start and short trips is also introduced. With this approach, test distances below 16 km, which are currently partially (possibly via AES) or not controlled in Euro 6 legislation, can now be (in the recommended EURO 7) both allowed and controlled. The budget must be calculated from the mg/km value (and the reference distance) applied to the same pollutant. This enables “one single limit” to be applied to light-duty testing. In addition, this guarantees continuity between the budget and the per km limit and avoids creation of gaps with the associated risks of ambiguity and possible interpretation issues. Conversely, the option to apply any budget (mass limit) to any distance, followed by any per km limit is not acceptable, since it risks creating exactly the above ambiguity. The following sections and corresponding graphs give the background and rationale underpinning the selection of the reference distance and the limit values for the budget and constant (per km) limits (for the case of NOx emissions as an example).

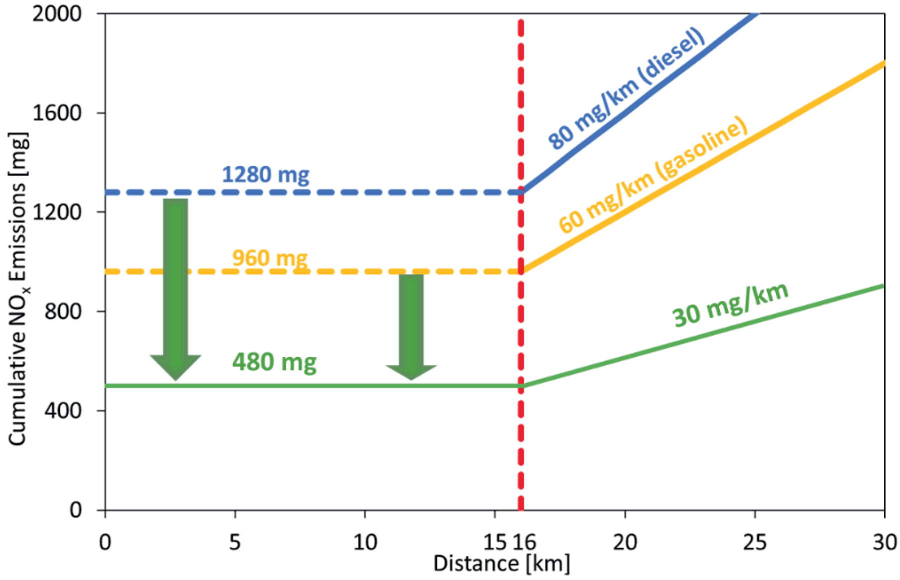


Figure 7-12: Recommended functional form of EURO 7 limits (example of NOx, scenario 1, normal conditions) in comparison to current Euro 6 approach (without conformity factor)

Focusing on the reference test distance i.e., the distance up to which the budget limit is applied, Figure 7-13 exemplifies the different options and our recommendation of 16 km. As in the previous Figure, this example refers to Scenario 1 for NOx emissions under normal conditions. The distance up to 2 km is illustrated as a separate area, as a reminder of the driving power restriction that is applied in normal conditions of use up to this distance (see section 6.2). As shown in Figure 7-13, for a budget of 480 mg (the selection of the exact value is justified in the following paragraphs based on analysis of Figure 7-14) if a reference distance lower than 16 km is selected, a higher limit in mg/km should be applied. For example, if a reference distance of 8 km is chosen, a limit of 60 mg/km should be applied for the rest of the cycle, which is equal to the lowest current Euro 6 limit without any conformity factor and does not fulfil the target for lower limits in EURO 7 compared to the current ones. Thus, the recommended reference distance of 16 km was selected to allow both low limit values in mg/km and a reasonable budget limit, which can be achieved by the EURO 7 technology packages presented above. Moreover, the selection of 16 km keeps the continuity with Euro 6 and guarantees transparent comparison of the recommended

[18] Although the discussion here is generic the Scenarios referred to are the ones developed a few paragraphs below in the text

emission limits with the past ones. A possible alternative to 16 km reference distance is further discussed in the following paragraphs in combination with the determination of the budget and constant limit values.

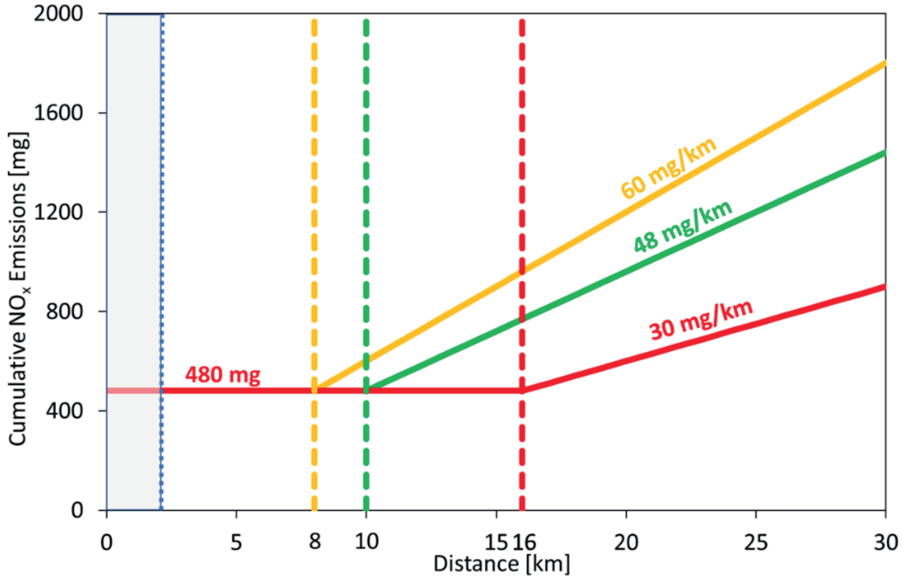


Figure 7-13: Definition of reference distance – example of NOx, scenario 1, normal conditions

Regarding the selection of the recommended budget and limit values (480 mg and 30 mg/km in the case of NOx emissions), Figure 7-14 to Figure 7-18 give a better insight to this topic for normal and extended conditions. As discussed in the previous section, the moderate RDE test at 23°C is used as an approximation of normal conditions and the Euro 6 worst-case RDE at -10°C for the extended conditions of use. The data of the coloured lines included in the graphs were derived from the simulation runs on the petrol and diesel technologies that underpin the selection of scenarios discussed in Section 7.1, while the green area corresponds to the emission limit range when an extra margin is added in order to account for the possible boundary conditions within normal and extended driving conditions and the measurement uncertainty of future portable equipment (more details for the uncertainty can be found in section 3.5). These boundary conditions are not covered by the above-mentioned proxy cycles and refer to all testing conditions described in Chapter 6, e.g., in terms of ambient temperature, altitude and driving dynamics. Taking driving dynamics as an example, the moderate RDE does not reach the maximum allowable power metric value (15%), thus this extra margin is introduced to cover this gap. It should also be noted that in the case of extended conditions (Figure 7-17) these simulation results do not include the effect of trailer towing.

Focusing on the selected technologies (details can be found in Table 7-5 to Table 7-7 and the respective descriptions well as in Section 7.3), Scenario 1 is based on G4, which corresponds to a petrol mHEV (without EHC) and D2 which refers to a diesel mHEV with EHC. As already discussed above, it is expected that for this scenario, almost no conventional (without any level of electrification) technology can survive (would be expected to be compliant with the limit values), while it should also be noted that the recommended diesel package (D2) may be too expensive for smaller vehicles e.g. A or B- segment. The recommended emission limits scenarios for Scenario 2 are based on a different technology mixture which comprises petrol mHEV with EHC (G5) and diesel mHEV with EHC and preheating (D3) while PHEV emission performance is also considered here.

The main outcome of this analysis is that for the case of Scenario 1 under normal conditions, as illustrated by the green area, a NO_x emission limit comprising a constant limit at 30 mg/km and a budget of 480 mg at a reference distance of 16 km is a major balanced step forward compared to Euro 6 and is expected to be possible to meet using possible future technologies within the range of the recommended test conditions.

At this point it should be noted that the recommendation of 480 mg budget, 30 mg/km constant limit and 16 km reference distance is the outcome of a rather complex exercise which incorporates several tuneable parameters e.g., the technologies expected in EURO 7 and their emission reduction potential under various test conditions. Thus, alternative approaches could be followed, and alternative recommendations made, if these parameters are varied. For example, a lower budget value could be introduced if technology permits this. This can also lead to different recommendations for the emission values and/or reference distance. A potential alternative combination could be the introduction of a reference distance of 10 km and a corresponding budget of 300 mg keeping the constant limit at 30 mg/km, as shown in Figure 7-16. This combination would require a greater reduction of cold start emissions compared to the option of 16 km reference distance and 480 mg budget.

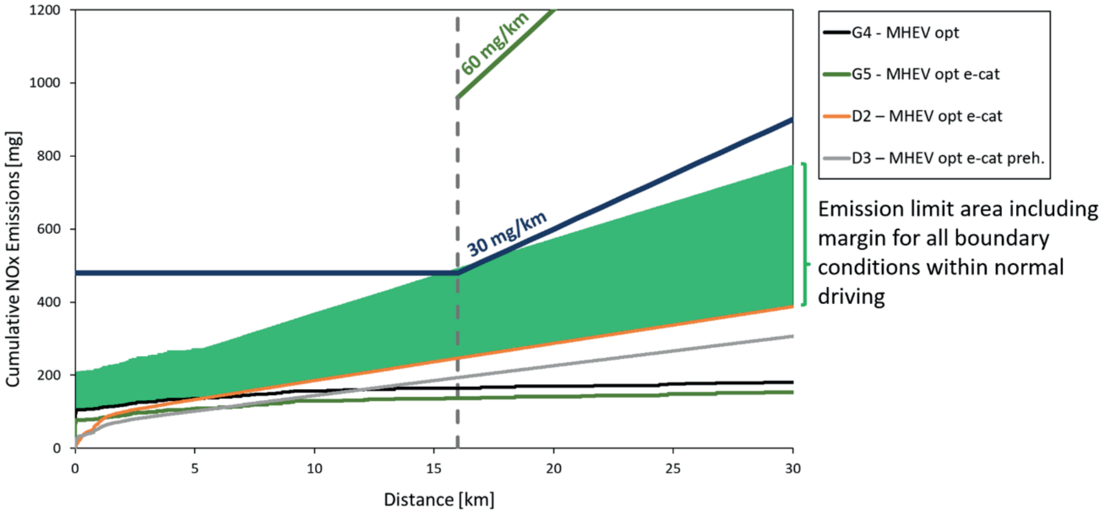


Figure 7-14: Emissions performance from simulation data over moderate RDE tests at 23ºC – Scenario 1.

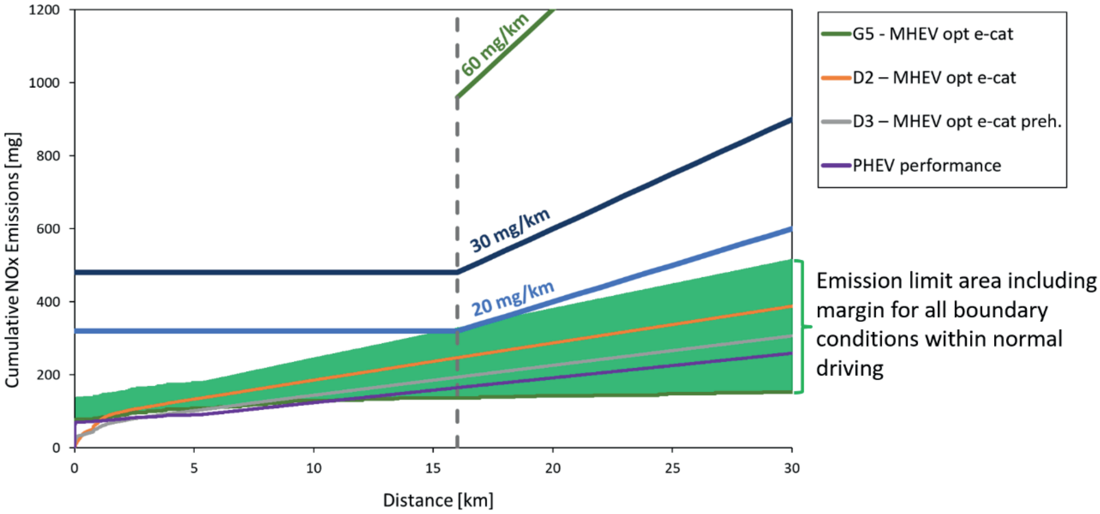


Figure 7-15: Emissions performance from simulation data over moderate RDE tests at 23ºC – Scenario 2

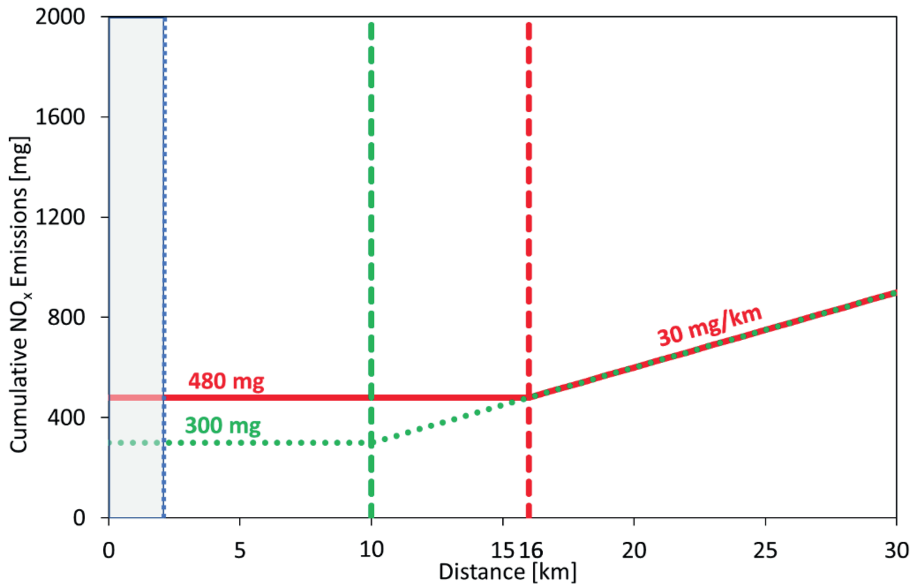


Figure 7-16: Alternative options for reference distance and corresponding budget – example of NOx, Scenario 1, normal conditions

Figure 7-17 and Figure 7-18 provide additional information on the multiplier recommended to be applied on the emission limits for the extended conditions of use. More specifically, as illustrated by the upper boundary of the green area, which includes all the possible boundary conditions (excluding trailer towing) within extended conditions, the recommended ×3 multiplier can be justified for both Scenarios 1 and 2.

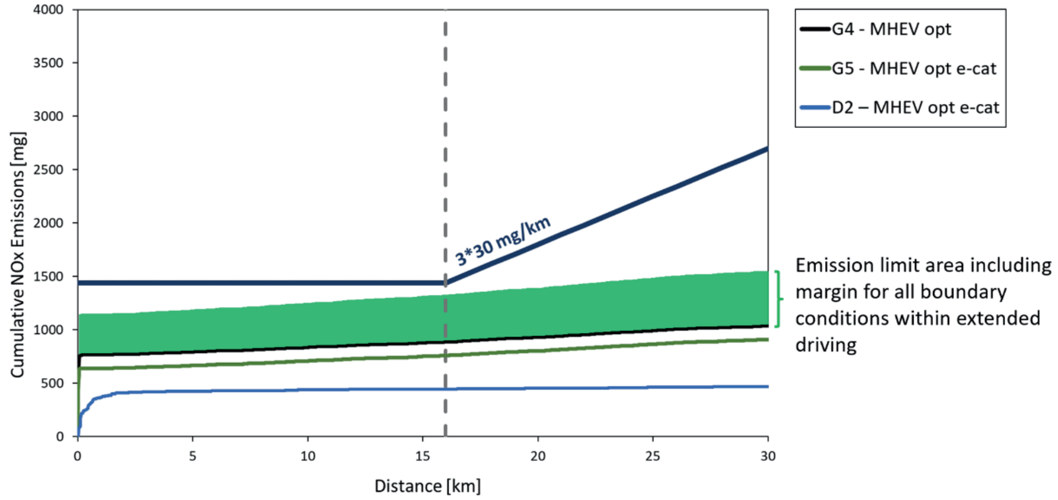


Figure 7-17: Emissions performance from simulation data on worst-case RDE tests at -10ºC (without trailer towing)-Scenario 1.

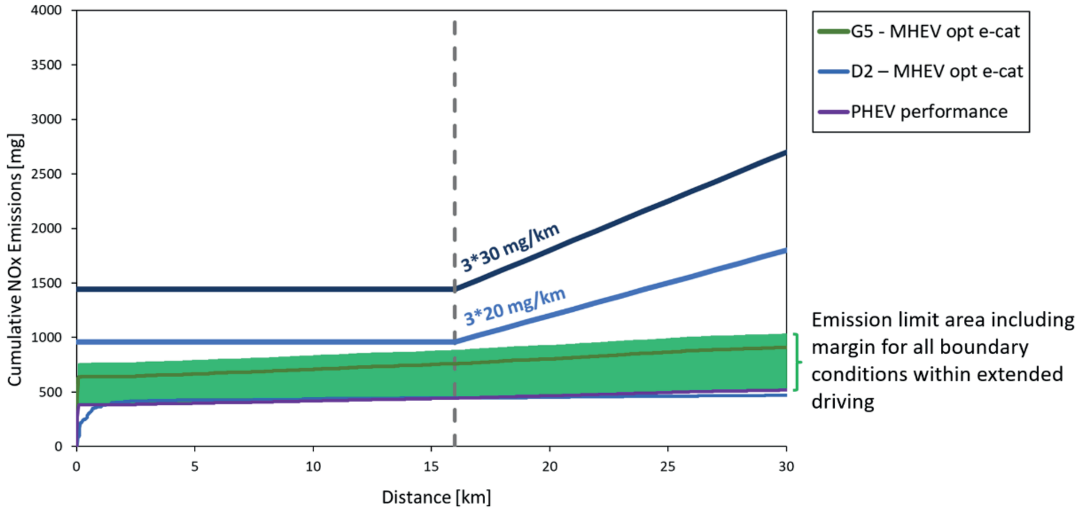


Figure 7-18: Emissions performance from simulation data on worst-case RDE tests at -10ºC (without trailer towing) – Scenario 2.

Figure 7-19 to Figure 7-21 provide a broader comparison of the emissions ratio between normal and extended conditions for both current technologies (measurement data from dedicated test campaign performed by JRC) and EURO 7 technology packages (simulation data as presented in section 7.3) for NOx, CO and HCs. Following the analysis presented in section 7.2, results are presented on the selected approximation test cycles for normal and extended conditions (moderate RDE and worst-case RDE respectively). As expected, the emission ratio between normal and extended conditions varies significantly among the different technologies and pollutants:

- For NOx emissions the multiplier is found to be ×3.1 from the Euro 6 measurements and ×4.2 from the EURO 7 simulations
- For CO emissions the multiplier is found to be ×4.1 from the Euro 6 measurements and ×2.2 from the EURO 7 simulations

- For HC emissions the multiplier is found to be ×4.7 from the Euro 6 measurements and ×8.1 from the EURO 7 simulations

To transpose these ratios of emissions performance to ratios of emissions limits we should account for the difference in the distances of the approximation cycles to the limits. This leads to approximately halving the above ratios when cycle-average emissions of the approximation cycles moderate RDE (approx. 50 km) and worst-case RDE (approx. 100 km) are taken into account. Thus, a generic (applicable to all technologies and pollutants) multiplier of ×3 is recommended. This ratio is considered to cover an as wide as possible range of the recommended testing conditions, without adding additional complexities in the regulation, while at the same time putting some additional challenge to the technology development.

A few points to be clarified as regards the multiplier for extended conditions can be summarised as follows:

- The ×3 multiplier is recommended to be applied if one condition falls within the extended conditions
- If more than one conditions fall within extended conditions (e.g., low temperature and trailer and high altitude), the ×3 multiplier is recommended to be applied only once
- Recommended application of the ×3 multiplier:
  - within budget distance (16 km): if any condition falls within extended conditions once, the ×3 factor is applied in the whole budget
  - beyond 16 km: the ×3 factor is applied only during the extended conditions period, not for the complete test. The exact implementation method/approach is to be defined.

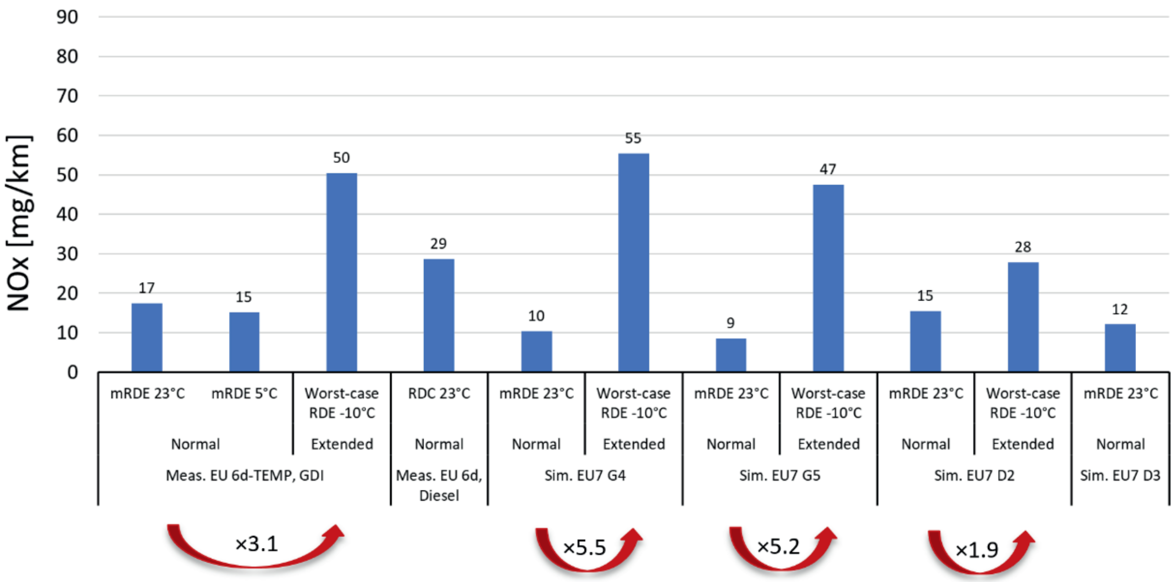


Figure 7-19: Measurement and simulation NOx results of different vehicles/technologies under indicative tests within normal and extended conditions. Results refer to 16 km for each cycle.

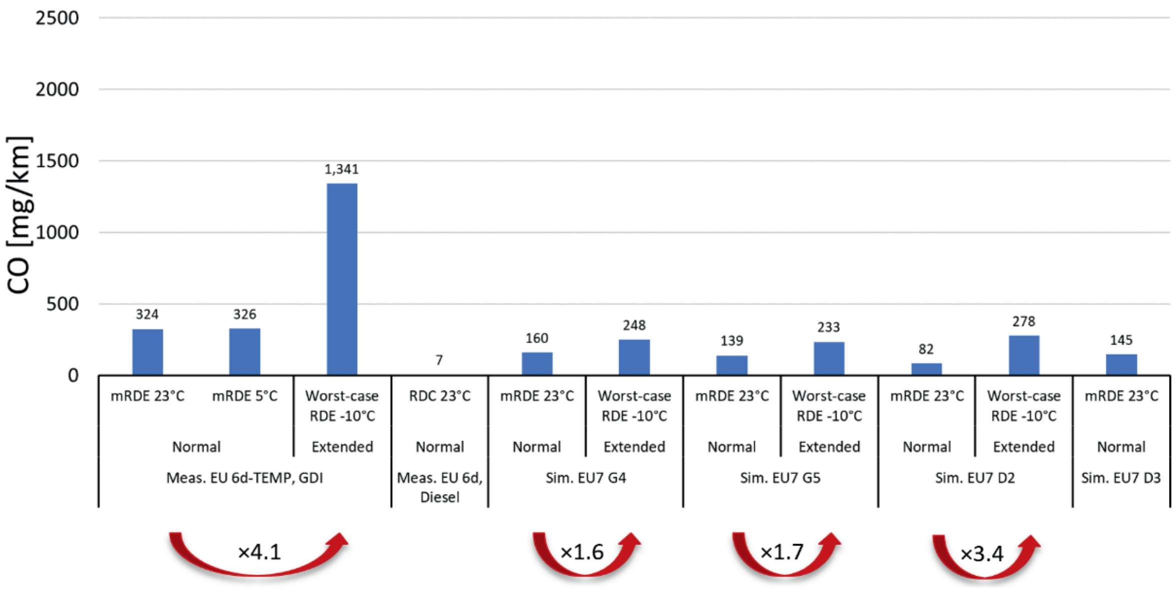


Figure 7-20: Measurement and simulation CO results of different vehicles/technologies under indicative tests within normal and extended conditions. Results refer to 16 km for each cycle.

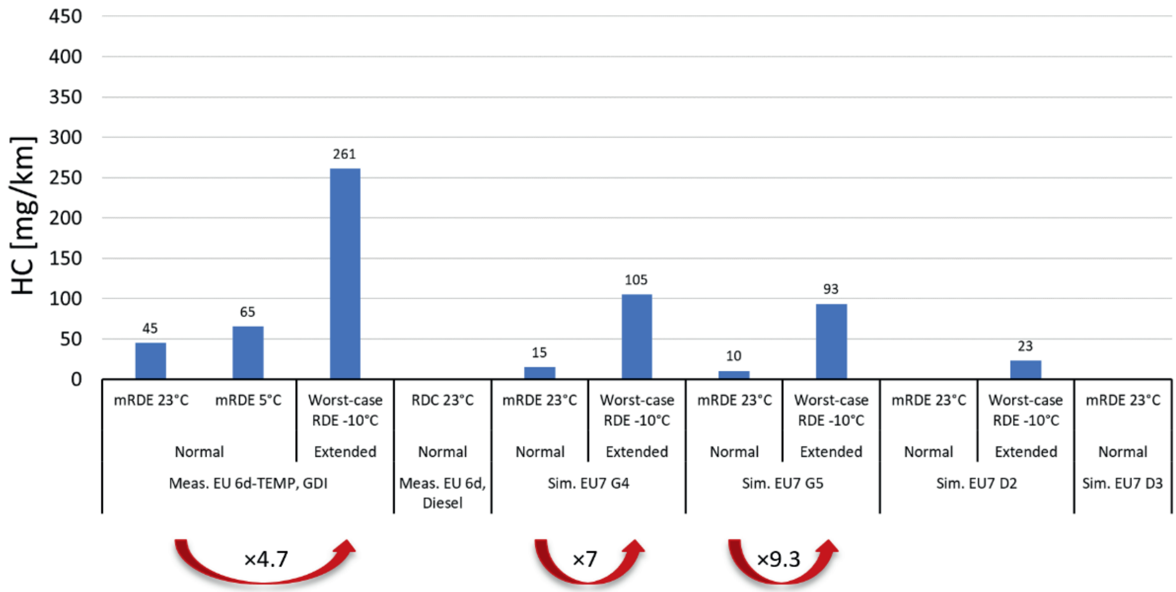


Figure 7-21: Measurement and simulation HC results of different vehicles/technologies under indicative tests within normal and extended conditions. Results refer to 16 km for each cycle

The above-presented approach was followed for the cases that simulation data were available i.e., for NOx, CO, THC (used as basis for the determination of NMOG emissions) and PN emissions. The recommended EURO 7 limit scenarios for the other pollutants were derived based on the available test data in CLOVE database, an engineering assessment for the expected EURO 7 performance and input from stakeholders on the expected performance of EURO 7 technologies, while the current and future limits in other countries/regions were also taken into consideration. A particular case is N_2O and CH_4 which, as discussed in Chapter 3, can be regulated as GHGs or as air pollutants. The final recommendation, in agreement with the EC, is to regulate them as air pollutants, and that the recommended limits in this case are set as a cap to avoid high polluters that are currently identified in some cases.

Figure 7-22 to Figure 7-24 show the evolution of cumulative N_2O, CH_4 and NH_3 emissions over several test cycles within normal conditions of selected Euro 6d and 6d-temp vehicles included in CLOVE database. All tests were performed on chassis dynamometer, as no portable equipment was available for these species. These tests are not exhaustive in terms of extreme testing conditions within normal conditions but cover a wide range of those e.g., in terms of ambient temperature. For each pollutant, the technologies that are expected to face the greatest challenges in EURO 7 are presented, i.e., diesel vehicles for N_2O emissions, petrol for NH_3, while all three fuels (CNG, diesel, petrol) are included in the case of CH_4 (among those CNG vehicles are facing the greatest challenges of course). Two emission limit levels that were considered in this investigation (10 and 20 mg/km) as well as the respective budget values are illustrated in the same graphs.

In the case of N_2O emissions – Scenario 1, a limit of 20 mg/km and a budget of 320 mg were selected as cap values, taking also into consideration the challenges that the combination of low NOx and low N_2O emission levels brings. These values are already achievable by some of the current technologies under several test conditions, while further improvements are expected in EURO 7, as described in section 7.1. CH_4 emissions vary greatly among the different technologies and test conditions, while in most cases cold start is found to be the main contributor. Again, a limit of 20 mg/km and 320 mg budget are selected as cap values for Scenario 1. It is suggested that these values are adopted if individual limits are applied separately for N_2O and CH_4. As an alternative to individual limits, a combined N_2O+CH_4 limit is also suggested. This limit is recommended to be lower than the sum of the individual limits and could prove beneficial for some technologies that face challenges in one of the two pollutants while maintaining low levels of the other. For example, as mentioned above, an N_2O emission limit may be difficult to achieve by some diesel vehicles under specific test conditions (e.g., when high NO_x reduction efficiency is needed), while CH_4 at the same conditions can be better controlled.

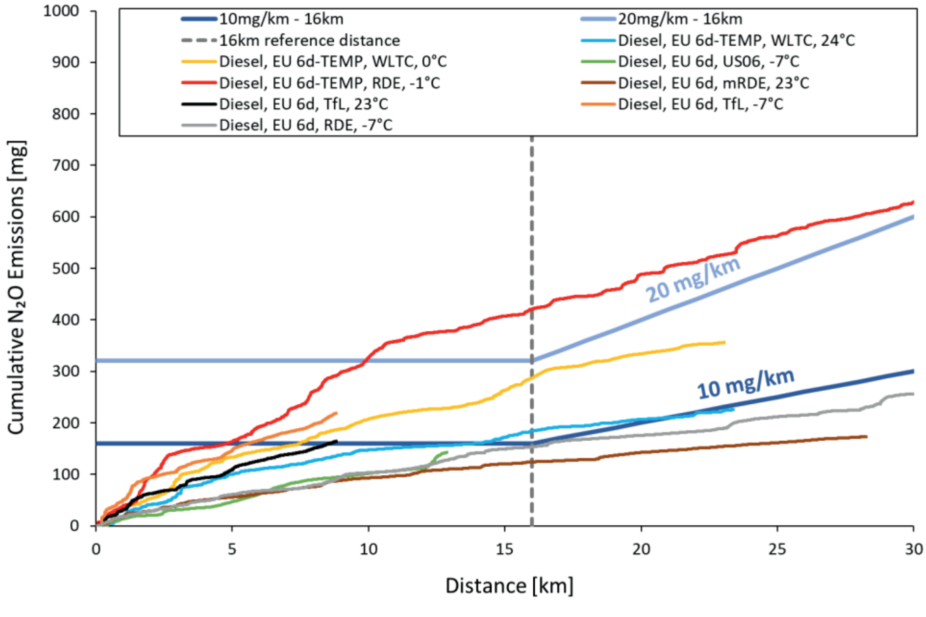


Figure 7-22: N_2O emission performance of selected vehicles and test cycles included in CLOVE database

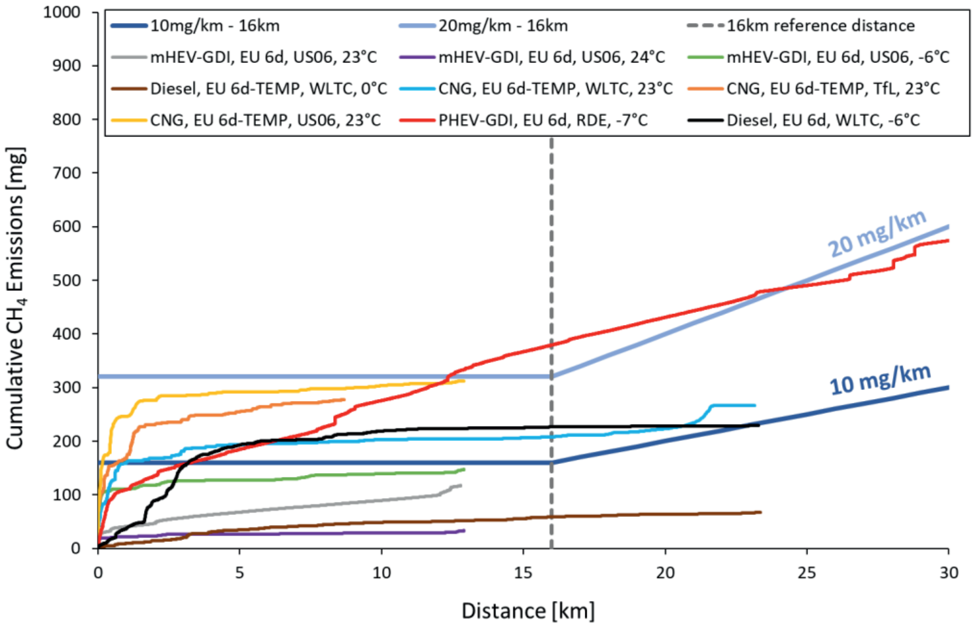


Figure 7-23: CH_4 emission performance of selected vehicles and test cycles included in CLOVE database

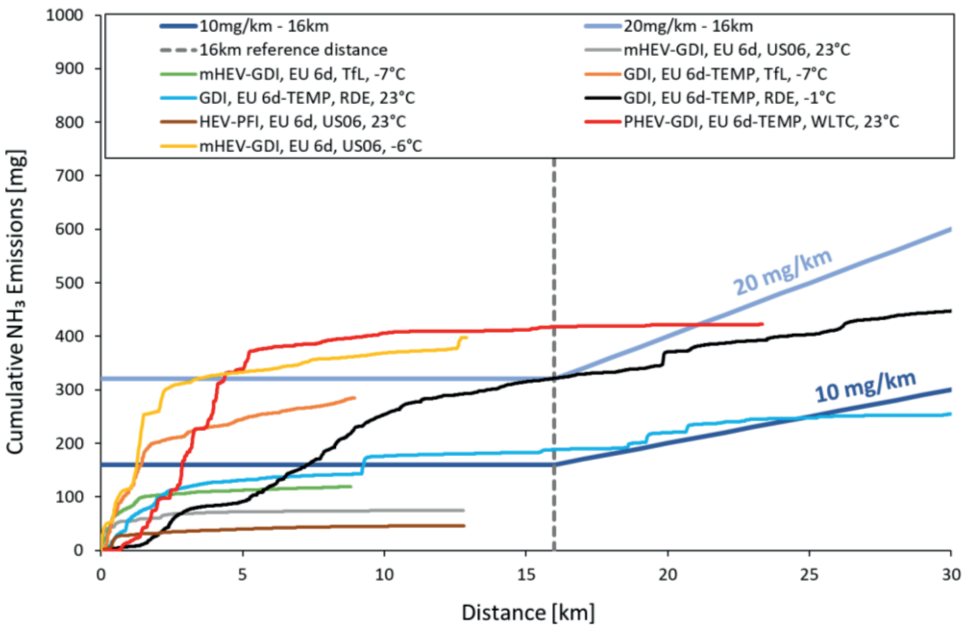


Figure 7-24: NH_3 emission performance of selected vehicles and test cycles included in CLOVE database

In the case of NH_3 emissions, a different approach was followed. A limit of 10 mg/km and a respective budget of 160 mg are recommended in this case, although as shown in Figure 7-24 this is very difficult to achieve for some current petrol vehicles under a wide range of test conditions. However, it is considered that the installation of an ASC in EURO 7 vehicles (a technology that is not widely used in Euro 6 petrol vehicles) may bring adequate reductions in tailpipe NH_3 emissions.

7.5 Recommended emission limits

The emission limits scenarios recommended for cars and vans for EURO 7 under "normal conditions" are presented in Table 7-8 below. The recommended limit values correspond to durability requirements of 160 000 km and 8 years since all calculations and assessments were based on deteriorated components to the current durability requirement. Further deterioration factors will possibly be recommended to cover the mileage up to 240 000 km. These factors are expected to be provided by an on-going parallel project. Based on a first engineering assessment a deterioration of 20% is expected from 160 000 to 240 000 km.

As regards PN emissions, the recommended EURO 7 limits correspond to a size cut-off of 10 nm, while the performance evaluation of prospective EURO 7 technologies, as presented in section 7.3, was based on SPN_{23} data. An SPN_{10}/SPN_{23} ratio in the range 1.1-1.3 (depending on the different filter technologies and test conditions) was considered in this case. This ratio was based on the performance of current state-of-the-art technologies as well as on engineering assessment for the expected EURO 7 technologies. As regards current technologies, the findings of the H2020 DownToTen[19] project as presented in a recent publication (Samaras Z. et al., 2021) indicate that the SPN_{10}/SPN_{23} ratio is 1.3 and 1.4 in latest-technology DPF-diesel and GPF-GDI vehicles respectively. Higher ratios were observed in vehicles without particulate filters, but these are not included in the EURO 7 technologies evaluated in this study. In addition, results from the H2020 SUREAL-23[20] project show that this ratio is in the range 1-1.3 for EURO 6d GPF-GDI vehicles. A recent study performed by the JRC (Lähde T. et al., 2021) showed that for GPF-GDI vehicles the sub-23nm (down to 10nm) fraction as a function of SPN_{23} emissions varied from 19% to 26%.

Table 7-8: Recommended emission limits for cars and vans for normal conditions for Scenarios 1 and 2

Pollutant	CO	NMOG	NOx	PM	PN_{10}	NH_3	CH_4	N_2O	HCHO
Unit	mg/km	mg/km	mg/km	mg/km	#/km	mg/km	mg/km	mg/km	mg/km
Scenario 1									
Cars and Vans	400	45	30	2	1×10^{11}	10	20	20	5
Vans with TPMLM > 2500 kg & PWR<35 kW/t	600	45	45	2	1×10^{11}	10	20	30	10
Scenario 2									
Cars and Vans	400	25	20	2	1×10^{11}	10	10	10	5
Vans with TPMLM > 2500 kg & PWR<35 kW/t	600	25	30	2	1×10^{11}	10	10	15	10

Note for N_2O and CH_4: alternatively, a combined N_2O+CH_4 limit < sum of the individual limits can be applied.
Note for Scenario 2 for CH_4 for Vans with TPMLM>2500 kg and PWR<35 kW/t: the recommended minimum limit based on future PEMS analyser capabilities is 14 mg/km (Table 3-7). The recommended limit of 10 mg/km will require further developments and/or improvements of portable systems.

[19] http://www.downtoten.com/

[20] http://sureal-23.cperi.certh.gr/

Table 7-9: Recommended budget emission limits (at 16 km reference test distance) for cars and vans for normal conditions for Scenarios 1 and 2

Pollutant	CO	NMOG	NOx	PM	PN_{10}	NH_3	CH_4	N_2O	HCHO
Unit	mg	mg	mg	mg	#	mg	mg	mg	mg
Scenario 1									
Cars and Vans	6400	720	480	32	16×10^{11}	160	320	320	80
Vans with TPMLM > 2 500 kg & PWR<35 kW/t	9600	720	720	32	16×10^{11}	160	320	30	160
Scenario 2									
Cars and Vans	6400	400	320	32	16×10^{11}	160	160	160	80
Vans with TPMLM > 2 500 kg & PWR<35 kW/t	9600	400	480	32	16×10^{11}	160	160	240	160

Note for N_2O and CH_4: alternatively, a combined N_2O+CH_4 limit < sum of the individual limits can be applied.

7.5.1 Comments and clarifications on recommended limits

Limits for LCVs: An artificial separation between N1 and M1 is no longer needed. Many N1 vehicles have twins in M1, for example, taxi vans and campers. The only exception is the low-powered LCVs, which are unique in their GVW and power and therefore usage. This was also recognised in RDE4 (EC/2018/1832), and testing was restricted for these vehicles. If such vehicles are tested in the same manner as all light duty vehicles, i.e., lifting boundary conditions, the emission limit should be appropriately higher, as this testing is more demanding for such vehicles. The sole criteria for this separate class of true LCVs (or "small HD") is TPMLM > 2500 kg and PWR < 35 kW/t (TPMLM-based and continuous system power). Figure 7-25 illustrates a few examples of real Euro 6 vehicles within a range of TPMLM and PWR, indicating the low-power and heavy LCVs that are recommended to be included in a separate true LCV class with higher limit values. As shown in Table 7-8 (Scenario 1) the recommended LCVs emission limits for CO, NOx and N_2O are 50% higher compared to the respective limits of passenger cars (HCHO limits are two times higher). The ×1.5 multiplier is derived from the ratio of current Euro 6 limits in N1-Class III compared to M1 and takes into account the expected improvement in EURO 7 technologies. No extra allowance is applied in the case of NMOG, NH_3, CH_4, PM and PN emissions, as it is expected that EURO 7 technologies will be able to control emission levels of these species in a similar manner as in Euro 6. For NH_3 for example, which is expected to be an issue only for the petrol vehicles, the installation of an ASC can bring emission levels well below the recommended limits. PM and PN emissions in particular can be well controlled if high filtration efficiency filters are installed as further explained in the respective section below.

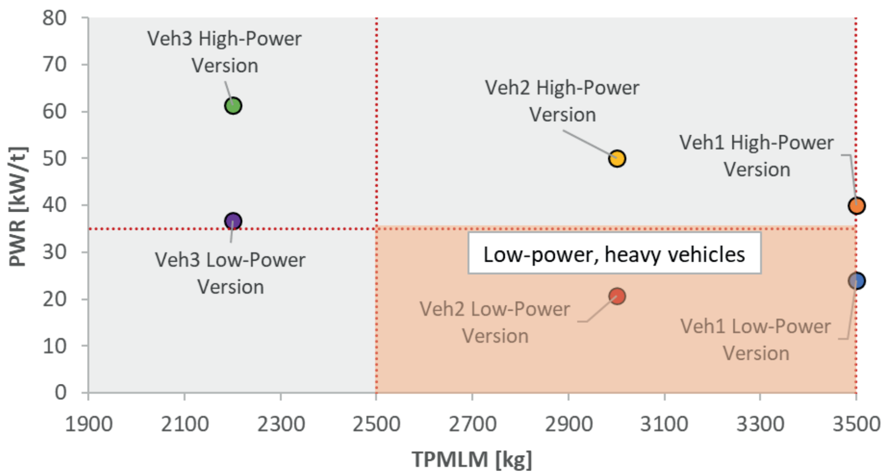
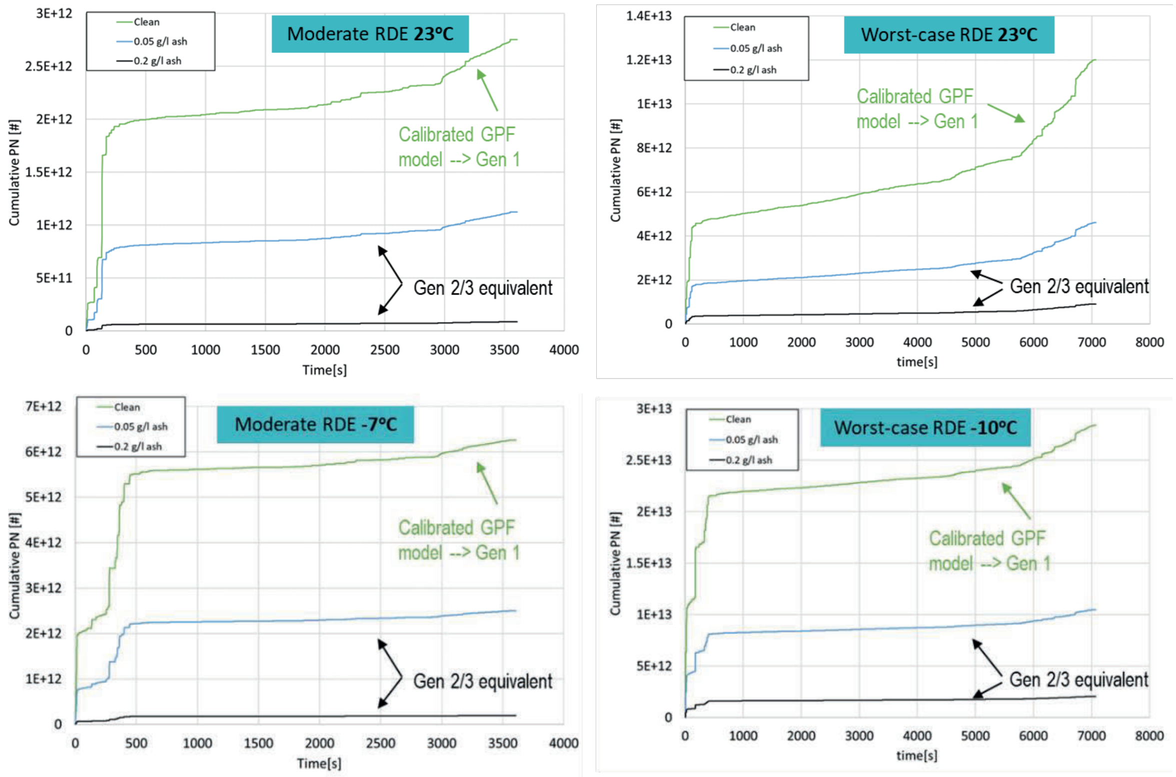


Figure 7-25: Example vehicles within a wide range of TPMLM and power-weight ratio

GPF filtration efficiency: The recommended EURO 7 limits require an improvement of GPF and DPF filtration efficiency, especially when they are at clean state. Focusing on GPF, increased filtration efficiency can be achieved either by new filter technology (new filter generation e.g., (D. Thier, 2020)) or by ash accumulation in the filter wall. The latter brings a continuous increase of filtration efficiency through the filter lifetime, i.e., a “negative” deterioration.



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5.

Figure 7-26: Evolution of cumulative PN emissions for different filters and test conditions

Figure 7-26 presents the results (under moderate and worst-case RDE at various ambient temperatures) of a simulation-based investigation that was performed in order to identify what current and new filter generations can achieve in terms of filtration efficiency. Three different cases are presented which can be translated to either different ash loadings (from clean filter up to 0.2 g/l ash) or different filter generations. Results for generation 1 technology or clean filter were derived from a measurement based calibrated GPF model, while generations 2 and 3 were approximated assuming an initial ash loading in the wall.

Table 7-10 to Table 7-13 present PN emissions of the test cases investigated. Focusing on the emission performance at 16 km, it can be observed that 2nd generation filters can reach emission levels well below the recommended limits for both moderate and worst-case cycles. When low temperature cycles are taken into account (i.e., moderate RDE at -7^{o}C and worst-case RDE at -10^{o}C) more advanced filters (3rd generation) are needed to reach the recommended emission levels (1×10^{11} p/km and 3×10^{11} p/km for moderate and extended conditions respectively). An important parameter in this analysis is the level of engine-out emissions. Apart from the high-efficiency filters, engine measures (e.g., increased fuel injection pressure, accurate lambda 1 control) will also be needed for very low tailpipe emissions (in the order of 10^{9} p/km).

Table 7-10: PN emissions of the different test cases under moderate RDE at 23^{o}C

Moderate RDE 23^{o}C	PN emissions [p/km]		Filtration efficiency [%]	
Test case	**Total cycle**	**16 km**	**Total cycle**	**16 km**
Clean filter / Gen 1	5.6×10^{10}	1.4×10^{11}	76	75
0.05g/l / Gen 2	2.3×10^{10}	5.5×10^{10}	90	90
0.2 g/l / Gen 3	1.8×10^{9}	4.3×10^{9}	99	99
Engine-out	2.3×10^{11}	5.5×10^{11}	-	-

Table 7-11: PN emissions of the different test cases under moderate RDE at -7^{o}C

Moderate RDE -7^{o}C	PN emissions [p/km]		Filtration efficiency [%]	
Test case	**Total cycle**	**16 km**	**Total cycle**	**16 km**
Clean filter / Gen 1	1.3×10^{11}	3.6×10^{11}	76	76
0.05g/l / Gen 2	5.1×10^{10}	1.4×10^{11}	91	90
0.2 g/l / Gen 3	4.0×10^{9}	1.1×10^{10}	99	99
Engine-out	5.4×10^{11}	1.5×10^{12}	-	-

Table 7-12: PN emissions of the different test cases under worst-case RDE at 23°C

Worst-case RDE 23°C	PN emissions [p/km]		Filtration efficiency [%]	
Test case	Total cycle	16 km	Total cycle	16 km
Clean filter / Gen 1	1.2×10^{11}	3.4×10^{11}	63	63
0.05g/l / Gen 2	4.7×10^{10}	1.3×10^{11}	86	86
0.2 g/l / Gen 3	9.3×10^{9}	2.7×10^{10}	97	97
Engine-out	3.3×10^{11}	9.3×10^{11}	-	-

Table 7-13: PN emissions of the different test cases under worst-case RDE at -10°C

Worst-case RDE -10°C	PN emissions [p/km]		Filtration efficiency [%]	
Test case	Total cycle	16 km	Total cycle	16 km
Clean filter / Gen 1	2.9×10^{11}	1.4×10^{12}	65	65
0.05g/l / Gen 2	1.1×10^{10}	5.3×10^{11}	87	87
0.2 g/l / Gen 3	2.1×10^{10}	1.0×10^{11}	97	97
Engine-out	8.2×10^{11}	4.0×10^{12}	-	-

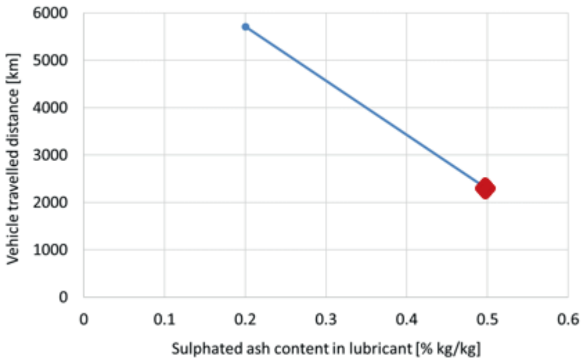

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Figure 7-27: Mileage to reach 0.05 g/l ash in GPF as function of oil properties

As mentioned above, ash accumulation in the filter is a continuous process leading to increased filtration efficiency over lifetime/mileage. It was attempted to correlate ash accumulation with mileage and define the minimum mileage until sufficient ash accumulation is reached (0.05 g/l was set as a target in this case). The following input data and assumptions were used:

- Sulphated ash content of engine oil 0.5% [kg/kg], as in ACEA European Oil Sequence 2016[21].
- Engine oil consumption selected 0.01 g/km (West, 2013) and

[21] https://www.acea.auto/publication/acea-oil-sequences-2016-july-2020-update/

- Ash recovery rate on GPF 70%.

As shown in Figure 7-27 a mileage of 2 500 km is estimated to be required in order to reach the desired ash accumulation in the case of lubricant sulphated ash content of 0.5% [kg/kg]. Thus, the CLOVE recommendation for a minimum mileage for valid testing under normal conditions is 3 000 km. Nevertheless, as mentioned above, ash accumulation highly depends on the testing conditions and engine parameters, therefore a wide variation of filtration efficiency can be observed especially within the first period of GPF lifetime. This can also be observed in the findings of the studies conducted by (Waters, et al., 2019)) and (Rose et al., 2020), which show a high variation of filtration efficiency from approximately 50% to 95% for the first 3 000 km and an increase of efficiency after this period (see Figure 7-28 and Figure 7-29). Thus, taking into account these findings, an alternative option to our recommendation (3 000 km) could be the introduction of a higher minimum mileage (e.g., 10 000 km), which is still lower than the current ISC requirements (15 000 km).

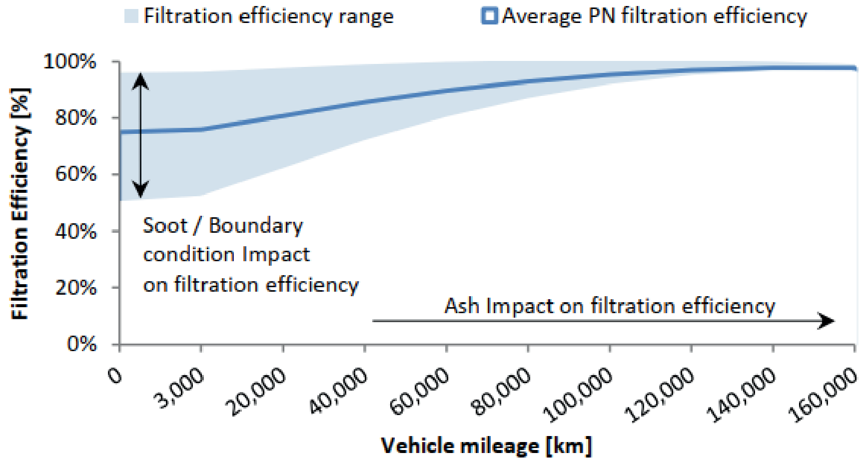

Figure 7-28: GPF filtration efficiency performance development over mileage (Waters, et al., 2019)

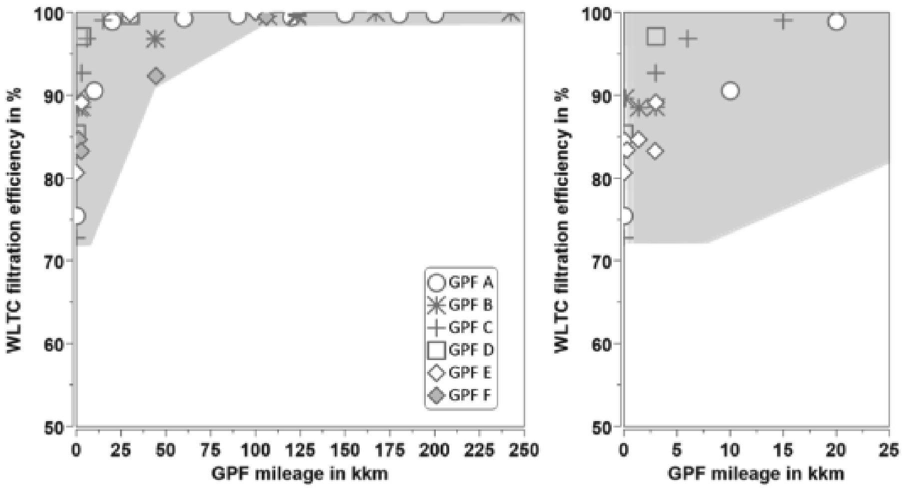

Figure 7-29: Filtration efficiency evolution of Generation 1 GPFs up to 250 000 km (left) and zoomed in for the first 25 000 km (right) (Rose et al., 2020)

DPF regeneration – PN emissions: As described in Chapter 4, tests including a DPF regeneration are recommended to be valid in EURO 7. Excess PN emissions (see discussion for other pollutants in section 2 of Annex 2) due to regeneration will be considered in the calculation of a weighted average emission factor which is determined based on the emissions levels of tests with and without regeneration and the DPF regeneration interval as follows:

$$PN\left[\frac{p}{km}\right] = \frac{PN_{regen\_cycle}\left[\frac{p}{km}\right] * d_{regen\_cycle}[km] + PN_{w/o\_regen}\left[\frac{p}{km}\right] * (regen\_interval - d_{regen\_cycle})[km]}{regen\_interval\,[km]}$$

7.

Where:

PN_{regen_cycle}: PN emissions during the test(s) that includes a DPF regeneration

d_{regen_cycle}: distance driven during the test(s) that includes a DPF regeneration

PN_{w/o_regen}: PN emissions during the test(s) without DPF regeneration

$regen\_interval$: interval between two consecutive DPF regeneration events

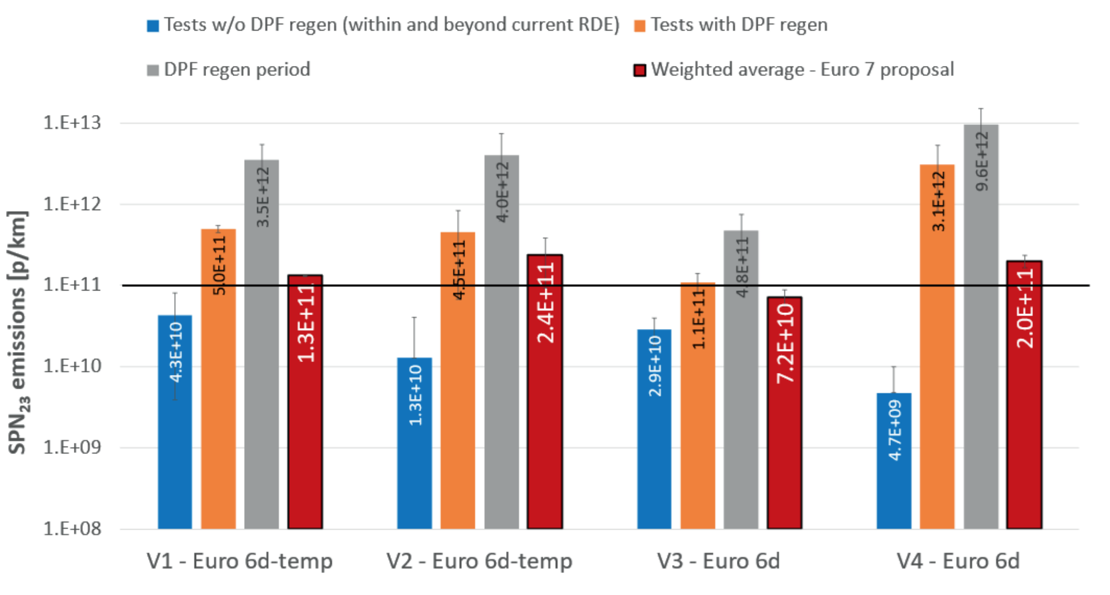

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Figure 7-30: Cycle-average SPN_{23} emissions over tests with and without DPF regeneration and recommended EURO 7 weighted average calculation.

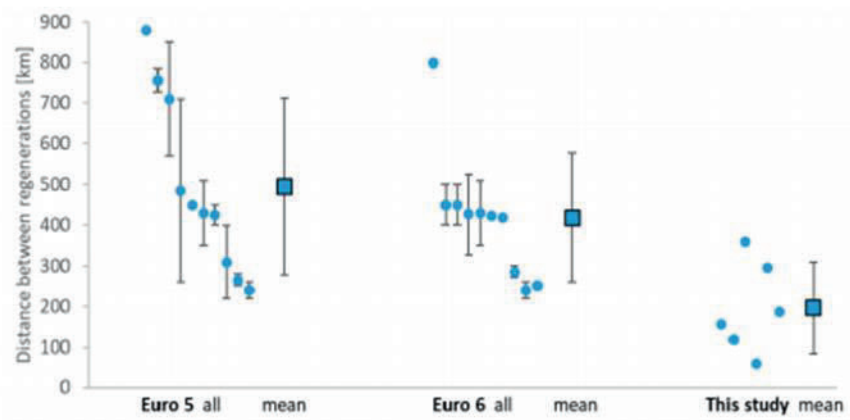

Figure 7-31: DPF regeneration interval base on a recent JRC study (Valverde and Giechaskiel, 2020)

Figure 7-30 presents the PN_{23} emission levels of the tests with and without DPF regeneration, the emission levels during regeneration period as well as the emissions calculated based on the above equation. These results refer to four Euro 6d-temp and 6d vehicles included in the CLOVE database. Weighted average emission levels are in the range 7.2×10^{10} – 2.4×10^{11} p/km, revealing that in most cases an improvement of DPF regeneration strategy and filtration efficiency of clean filters is needed so that tailpipe emissions comply with the recommended limit of 1×10^{11} p/km. Note that PN emissions in this analysis refer to PN_{23}. The contribution of sub-23 nm fraction on PN emissions is expected to be very small during regeneration (Giechaskiel, 2020), thus no significant change of the results is expected if PN_{10} is taken into account.

An important point for the calculation of the weighted average emissions is the determination of DPF regeneration interval i.e., the mileage from regeneration start until the next regeneration start. This is recommended to be derived by the OBM system and could be based on the last e.g., 10 regeneration events. For a new vehicle, the DPF regeneration interval should be declared by the manufacturer and this value will be constantly updated with mileage accumulation. Apart from regeneration interval, the OBM could inform the tester about the DPF regeneration start and end, as well as the estimated mileage until the next regeneration event. Finally, it is recommended that all this information is stored in the electronic control unit ECU, at least for the last 10 regeneration events. An analysis performed by JRC on several Euro 5 and Euro 6 vehicles as shown in Figure 7-31 reveals a significant variation among the different vehicles and a clear decrease of DPF regeneration interval over the latest technology vehicles. The results from the CLOVE database (Euro 6d-temp and 6d vehicles) as presented in Table 7-14 confirm that very DPF regeneration intervals are observed in some latest technology vehicles, although not in all cases.

Table 7-14: DPF regeneration interval based on CLOVE database vehicles

CLOVE database vehicles	Regeneration interval [km]
V1 – Euro 6d-temp	440
V2 – Euro 6d-temp	200
V3 – Euro 6d	145
V4 – Euro 6d	400

A similar analysis on the effect of DPF regeneration on NO_x and CO emissions (other pollutants not available as all tests were performed on road) was performed as a next step. The preliminary results of this investigation are presented in Annex 2, revealing that in 3 out of the 4 studied vehicles of the CLOVE database, the effect of driving dynamics (in terms of cycle-average emissions) is larger than the effect of DPF regeneration. This indicates that a weighted approach similar to that for PN emissions may not be necessary for gaseous emissions either. However, this should be further investigated focusing mainly on the evaluation of emission levels only during the actual DPF regeneration period.

7.5.2 Recommended technology scenarios

According to the previous analysis on potential future technologies, Table 7-15 lists the technology packages that comply with the recommended emission limits (based on the simulation results). It is clarified that the proposed technology packages correspond to both the emission limit scenarios (Scenario 1 – Balanced, Scenario 2 – Ambitious) presented above. In all cases, it is considered that all future vehicles will have a degree of electrification (from mild-hybrids to PHEVs), imposed by the CO_2 emission targets. In addition, the request to fulfil more ambitious targets under demanding operating conditions may boost the penetration of PHEVs, particularly in the larger vehicle segments, taking advantage of their capability for zero-emission operation.

Table 7-15 Technology packages that comply with recommended emission limits (Scenario 1 and 2)

Category	Petrol	Diesel	CNG
MHEV	G3 G4 G5 G6	D1 D2 D3	C1 C3 C4
PHEV	G8 G9 G10 G11	D4 D5	C5 C6 C7 C8

7.5.3 Cost of EURO 7 Technology Packages

This section examines the hardware costs associated with the technologies and technology packages examined in the section above. Hardware costs consist of costs arising from the need to fit engine control and emission control technologies fitted to vehicles to meet the tailpipe emission limits. Calibration costs are considered separately under the impact assessment study and are not examined here. In addition, electrification is considered to be forced by the CO_2 legislation and therefore cost increments associated with these components are not attributed to EURO 7 for these technology scenarios.

This section provides a summary of the sources used to underpin the incremental cost calculations for the technology packages examined for EURO 7. These sources comprise the cost estimates calculated for Euro 6d compliant technology packages (as part of the Euro 6/VI evaluation study), a comprehensive literature review of emerging technologies, and cost estimates provided by stakeholders over the course of the study. Overall, the review found limited cost data available within the literature and limited data was provided by stakeholders during the targeted stakeholder consultation conducted as part of the impact assessment study[22]. In response to the consultation, only four stakeholders provided incremental costs for the technologies specified across both LDVs and HDVs.

The total hardware costs (i.e., costs of technology installed in new vehicles) for Euro 6d vehicles, calculated as part of the Euro 6/VI evaluation study provided the main baseline against which the costs of EURO 7 technology packages were assessed. Following the introduction of Euro 6 RDE, the total hardware costs for Euro 6d vehicles are estimated to be €402-€465 for PI and €890-€1 703[23] for CI vehicles. The incremental costs expected as a result of EURO 7 were calculated from the unit hardware costs of individual components under Euro 6d Final provided by the evaluation. These include the costs of components such as NO_x sensors.

As well as providing their views regarding potential emission control systems to be compliant with future EURO 7 limits, stakeholders were also asked to estimate the cost of these emission control systems relative to the baseline of Euro 6d. In addition, stakeholders were given the opportunity to provide cost estimates for the example emission control

[22] The technoeconomic questions posed to stakeholders can be found in the Annex of this report

[23] Euro 6/VI Evaluation report

systems presented as a baseline for petrol and diesel cars and vans (see Table 7-1). The unit cost per system for technologies expected for inclusion in EURO 7 technology packages are presented in Table 7-16 below. This table includes the baseline unit costs per system for each technology as well as the estimated cost increment expected for EURO 7 provided by stakeholders, where these are available. Regarding the costs of technologies compliant with Euro 6d, only additional evidence regarding costs identified within the literature and as a result of the stakeholder consultation are presented here for context. Baseline costs associated with Euro 6d that result from the Euro 6/VI evaluation study are not presented in the table below, however as stated above, these form the core baseline for this technoeconomic assessment of EURO 7 technologies. Where necessary, due to confidentiality, these costs have been anonymised. Where there are uncertainties, these costs have been presented as ranges.

Table 7-16: Summary of costs available within the literature and from the 2nd targeted stakeholder consultation

Technology	Unit Cost [€] per system]	Euro 6d or above	Source
Diesel			
LNT	~ 320 – 509	Euro 6d, Controls NO_x (also HC versions) (cost of system)	Calculated from (Yang et al., 2015)
SCR	~ 494	Euro 6d (cost of system including urea system)	Calculated from (Yang et al., 2015)
EGR	~142 – 160	Euro 6d (cost of system including valve and cooler)	Calculated from (Yang et al., 2015)
EHC	1 200 – 2 500[a]	EURO 7 or equivalent (total cost increment from Euro 6d)	2nd Targeted Consultation
Petrol			
TWC	~ 40[b]	EURO 7 or equivalent (cost increment from Euro 6d)	2nd Targeted Consultation

[a] Total cost increment for EURO 7. Lower cost range includes 48V, while the upper range includes 400V.

[b] The increment appears to equate to an additional 0.5 g of palladium.

NB: Costs are shown in 2020 EUR, i.e., adjusting for inflation. Where upper and lower values were obtained, the average value is presented.

Catalyst	Unit Cost [€/g]	Source
Platinum	~ 31	Other; confidential
Palladium	~82	Other; confidential
Rhodium	~ 391	Other; confidential

NB: Costs are shown in 2020 EUR, i.e., adjusting for inflation. Where upper and lower values were obtained, the average value is presented.

Regarding the price of catalysts, one stakeholder noted concerns that the increase in demand expected to be incurred by EURO 7 may introduce upward pressure on the unit cost of rhodium in particular. In their 2021 outlook report, Johnson Matthey (2021) confirm that catalyst demand within the automotive sector is the primary driver of demand for rhodium and highlights the increase in demand as a result of the introduction of increasingly stringent measures in China for example and that rhodium is experiencing "significant structural deficit", with growth in demand exceeding supply over the last 5 years. Follow up interviews with stakeholders were also conducted to obtain additional information which provide direct inputs to the final costings outlined in the following section. Overall, when calibrating the final costs, one of the most important tasks in the estimation of the costs was the assumptions concerning catalyst sizing and components of the different technology packages.

Calculated incremental cost

The hardware cost that is associated with the EURO 7 technology packages is calculated as incremental cost to the latest Euro 6 technologies. This cost originates either in the adaptation/optimisation of existing technologies (e.g., increased volume of catalysts) or in the introduction of additional emission control technologies (e.g., NH_3 clean up catalyst in petrol vehicles, electrically heated catalyst etc.).

The first step in the cost estimate is the calculation of the cost of individual components/technologies. The second step is the determination of the cost of the technology packages, as these have been presented in Table 7-5, Table 7-6, and Table 7-7.

It is underlined that these costs refer to the tailpipe emission control. A separate table is provided for the cost of the evaporative emission control components in Chapter 9.

The first step of the procedure is the estimation of the individual component/technologies cost. The selection of the exact components is based on the previous analysis on technology packages. Table 7-17 presents the incremental cost of individual technologies and components foreseen in EURO 7 cars (the same hold also for vans, assuming larger engine capacities). With reference to specific technologies, the following are clarified:

- Hybridisation/electrification is enforced by the CO_2 policy. Here the additional cost considered is the one that is related to the necessary power electronics and the controller of the EHC.
- A particle filter is introduced in all CNG vehicles.
- The secondary air system is applied in the cases of preheating (either with an EHC or a burner) and when a NH_3 CUC is used.
- Multi gas sensors are considered for OBM only.

Table 7-17: Incremental cost of individual technologies/components for EURO 7 cars/vans

Technology/ Component	Variation	Vehicle segment	Change Euro 6d → EURO 7	Unit cost [€ or €/l]	Total cost [€]
Petrol / CNG					
Hybrid system	MHEV	All	—	40	40
	PHEV	All	—	40	40
TWC	+50% volume	Small	1.4l → 2.1l	80	56
		Medium	1.8l → 2.7l	80	72
		Large	2.2l → 3.3l	80	88
	Improved durability (+10% of total component cost)	Small	1.4l → 2.1l	80	16.8
		Medium	1.8l → 2.7l	80	21.6
		Large	2.2l → 3.3l	80	26.4
GPF optimisation	Bare optimised	All	0 → 1	10	10
	Coated optimised	All	0 → 1	15	15
GPF (introduction for CNG)	For CNG vehicles not already equipped with GPF	Small	0 → 1.4l	57	79.8
		Medium	0 → 1.8l	57	102.6
		Large	0 → 2.2l	57	125.4
e-cat 4kW (EHC)	without preheating	All	0 → 1	85	85
	with preheating	All	0 → 1	85	85
Fuel burner 15kW	without preheating	All	0 → 1	800	800
	with preheating	All	0 → 1	800	800
Secondary air injection	For cases with preheating	All	0 → 1	78	78
CUC for NH_3	Introduction in EURO 7	Small	0 → 0.7l	23	16.1
		Medium	0 → 0.9l	23	20.7

Technology/ Component	Variation	Vehicle segment	Change Euro 6d → EURO 7	Unit cost [€ or €/l]	Total cost [€]
		Large	0 → 1.1l	23	25.3
	Improved durability (+10% of total component cost)	Small	0 → 0.7l	23	1.6
		Medium	0 → 0.9l	23	2.1
		Large	0 → 1.1l	23	2.5
SCR (passive)	Introduction in EURO 7	Small	0 → 2.8l	30	84
		Medium	0 → 3.6l	30	108
		Large	0 → 4.4l	30	132
LNT	Introduction in EURO 7	Small	0 → 1.4l	42	58.8
		Medium	0 → 1.8l	42	75.6
		Large	0 → 2.2l	42	92.4
Multi-gas sensor	Introduction in EURO 7	All	0 → 1	200	200
OTA data transmission	Introduction in EURO 7	All	0 → 1	40	40
Diesel					
Hybrid system	MHEV	All	—	40	40
	PHEV	All	—	40	40
e-cat 4kW (EHC)	without preheating	All	0 → 1	85	85
	with preheating	All	0 → 1	85	85
Fuel burner 15kW	without preheating	All	0 → 1	800	800
	with preheating	All	0 → 1	800	800
Secondary air injection	For cases with preheating	All	0 → 1	78	78
DOC	+50% volume	Small	1.2l → 1.8l	42	25.2
		Medium	1.4l → 2.1l	42	30.2

Technology/ Component	Variation	Vehicle segment	Change Euro 6d → EURO 7	Unit cost [€ or €/l]	Total cost [€]
		Large	1.8l → 2.7l	42	37.0
	Improved durability (+10% of total component cost)	Small	1.2l → 1.8l	42	7.6
		Medium	1.4l → 2.1l	42	9.1
		Large	1.8l → 2.7l	42	11.1
SCR	+50% volume	Small	3.0l → 4.5l	30	45
		Medium	3.6l → 5.4l	30	54
		Large	4.4l → 6.6l	30	66
	Improved durability (+10% of total component cost)	Small	3.0l → 4.5l	30	13.5
		Medium	3.6l → 5.4l	30	16.2
		Large	4.4l → 6.6l	30	19.8
SCRF	+50% volume	Small	2.3l → 3.4l	55	61.9
		Medium	2.7l → 4.1l	55	74.3
		Large	3.3l → 5.0l	55	90.8
ASC	+50% volume	Small	0.8l → 1.2l	23	8.6
		Medium	0.9l → 1.4l	23	10.4
		Large	1.1l → 1.7l	23	12.7
	Improved durability (+10% of total component cost)	Small	0.8l → 1.2l	23	2.6
		Medium	0.9l → 1.4l	23	3.1
		Large	1.1l → 1.7l	23	3.8
Turbine bypass	Introduction in EURO 7	All	0 → 1	15	15
Multi-gas sensor	Introduction in EURO 7	All	0 → 1	200	200

Technology/ Component	Variation	Vehicle segment	Change Euro 6d → EURO 7	Unit cost [€ or €/l]	Total cost [€]
OTA data transmission	Introduction in EURO 7	All	0 → 1	40	40

In the second step, the total cost of the complete EURO 7 technology packages is calculated, by synthesising the cost of individual components, considering the share of each segment. The calculated costs are presented in Table 7-18 and are illustrated in Figure 7-32, Figure 7-33 and Figure 7-34. Finally, Table 9-5 (in Chapter 9) summarises the cost of the components that are used in the evaporative emission control technologies.

Table 7-18: Cost of each EURO 7 technology package for cars

Short name	Incremental cost compared to Euro 6d [€]
Petrol	
G1 – Base Euro 6	0
G2 – Base EURO 7 opt	109
G3 – MHEV Base Euro 6	0
G4 – MHEV EURO 7 opt	109
G5 – MHEV EURO 7 opt e-cat	234
G6 – MHEV EURO 7 opt e-cat 10s	335
G7 – MHEV EURO 7 opt burner 10s	1010
G8 – PHEV Base Euro 6	0
G9 – PHEV EURO 7 opt	109
G10 – PHEV EURO 7 opt e-cat	234
G11 – PHEV EURO 7 opt e-cat 60s	335
G12 – PHEV EURO 7 opt burner 30s	1010
G13 – PHEV EURO 7 opt e-cat 60s 8kW	828
CNG	
C1 – MHEV EURO 7 opt	79
C2 – MHEV EURO 7 opt GPF	165
C3 – MHEV EURO 7 opt e-cat	290
C4 – MHEV EURO 7 opt e-cat 10s	386

Short name	Incremental cost compared to Euro 6d [€]
C5 – PHEV EURO 7 opt	79
C6 – PHEV EURO 7 opt GPF	165
C7 – PHEV EURO 7 opt e-cat	290
C8 – PHEV EURO 7 opt e-cat 60s	386
Diesel	
D1 – MHEV P0 EURO 7 opt	202
D2 – MHEV P0 EURO 7 opt e-cat	327
D3 – MHEV P0 EURO 7 opt e-cat preheating	405
D4 – PHEV P2 EURO 7 opt	202
D5 – PHEV P2 EURO 7 opt e-cat	502

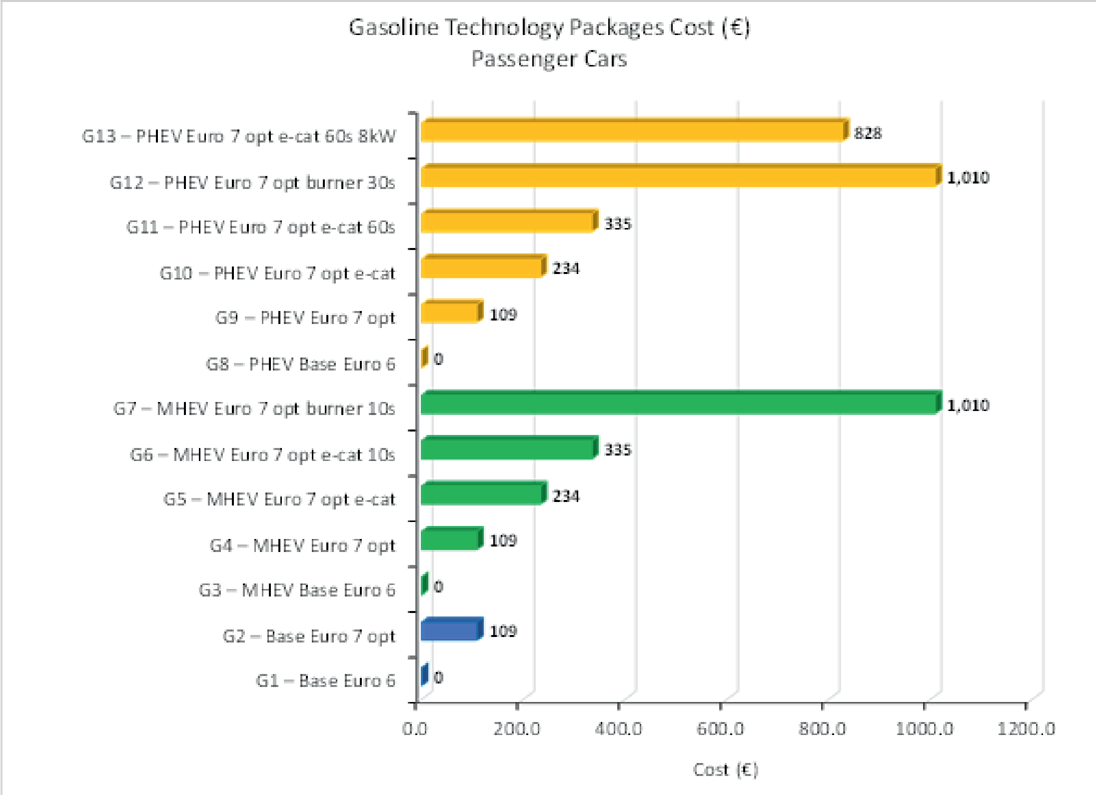

Figure 7-32: Incremental cost of EURO 7 technology packages for petrol vehicles

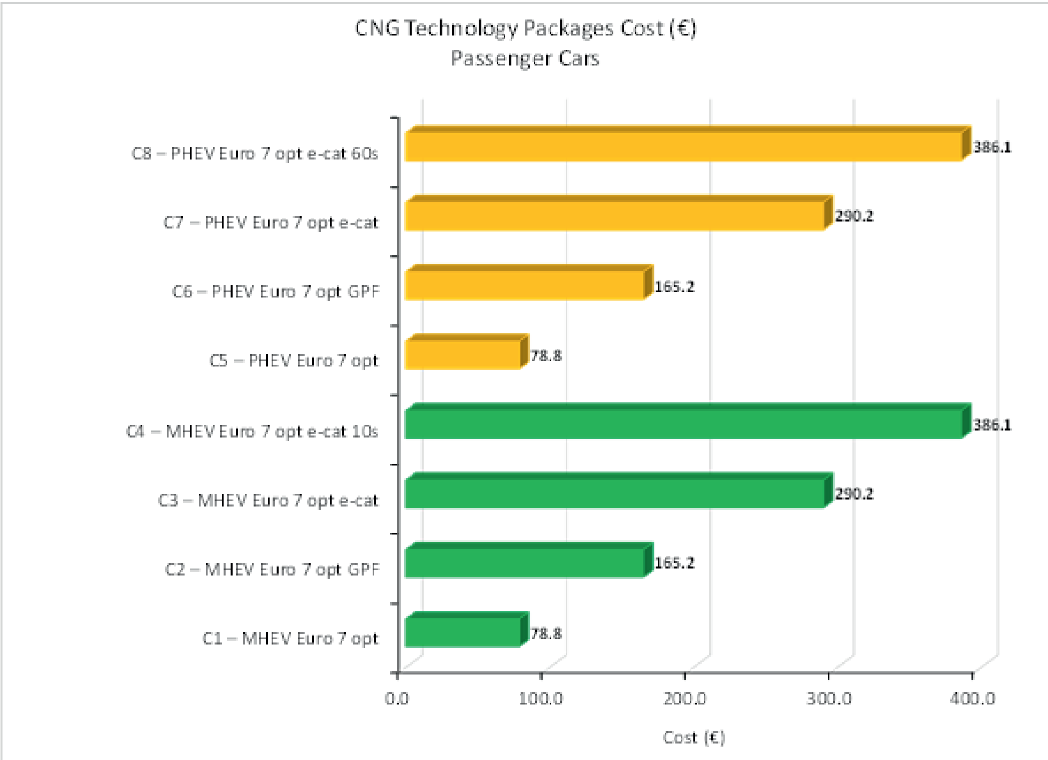

Figure 7-33: Incremental cost of EURO 7 technology packages for CNG vehicles

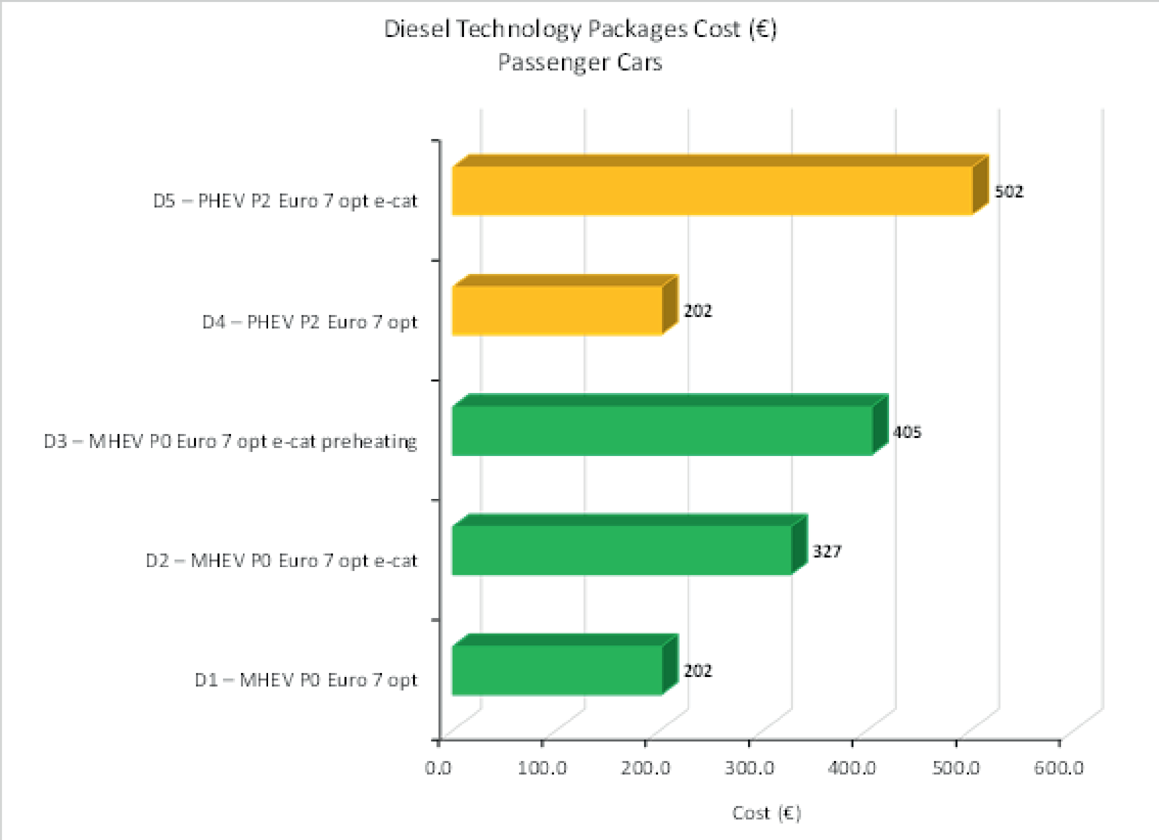

Figure 7-34: Incremental cost of EURO 7 technology packages for diesel vehicles

8 Recommended EURO 7 limits and technologies to meet them for lorries and buses (HDVs)

8.1 Assessment of potential future technologies

In total seven different EURO 7 technology scenarios have been elaborated which have different fuel and engine concepts on one hand and a different complexity of the exhaust gas aftertreatment on the other hand.

Fuels and engines covered:

D .... Diesel

C .... CNG or LNG in Otto- engines (stoichiometric combustion)

L .... CNG or LNG in diesel engines with diesel as pilot injection for ignition ("HPDI" engines)

For all engine concepts optimised strategies for fast heating of the EATs and low raw emissions during the heat-up phase have been assumed as the basis for EURO 7.

Exhaust gas aftertreatment:

1 .... Current diesel exhaust gas box

2 .... As 1 with additional close-coupled system with DOC, SCR and Ammonia Slip Catalyst (ASC) For Otto Engines a close-coupled TWC with OPF or 4WC is added to the current TWC system.

3. .... As 2 with preheating using a diesel burner

4. .... As 3 but as hybrid vehicle possibly using an E-Cat also for pre-heating in case of sufficiently large battery capacity at a PHEV.

The selection is based on a literature review[24], presentations made by industry to the Commission and to the CLOVE consortium (presentations from Bosch, AECC and JAMA and supporting material sent by Westport on HPDI engines) and finally also on experiences from engineers within the CLOVE consortium.

Most of the literature deals with meeting future CARB HDV standards and thus show technology packages leading to approximately 60 to 160 mg NOx/kWh in the cold FTP, 20 to 30 mg NOx/kWh in the hot FTP and 165 to 275 mg NOx in the CARB Low Load Cycle (LLC). Naber (2020) also provide test results for the WHTC in cold and hot conditions and report N_2O, NH_3, HC, CO and CH_4 test data alongside NOx. Weighted NOx emissions of this demonstrator engine are 17mg/kWh in FTP and 12 mg/kWh in the WHTC.

All concepts with low cold start and low load emissions use a close-coupled SCR in addition to the typical EURO VI underfloor exhaust aftertreatment box with DOC, DPF and SCR. Ammonia slip catalysts are typically mounted after each SCR. Some concepts use a close-coupled (cc) DOC upstream of the SCR, which increases the NO_2/NO ratio for better low temperature conversion. Other concepts work without the cc DOC to heat-up the SCR faster. Both concepts have specific advantages and disadvantages, mainly related to the thermal inertia of the systems and the ability of the engine to meet exhaust temperatures above ca. 500°C at the cc SCR needed for de-sulphurisation (deSOx) without DOC support. Current Vanadium based SCR systems have much lower N_2O formation potential as long as the exhaust gas temperature is below ca 400°C but lower low temperature NOx conversion than CU-Zeolite based SCR. Furthermore, Vanadium oxide can be released above ca. 550°C which is highly toxic. Introducing a temperature and/or V_2O_2 screening at full load, e.g., during the fuel consumption mapping test cycle could help to avoid possible

[24] (Gary, 2019), (Monschein, 2015), (MECA, 2019), (Hammer, 2020), (McCarthy, 2019), (C.a. Sharp, 2021), (Bosch, 2020), (Naber, 2020)

issues with Vanadium oxide emissions if low N_2O limits incentivise the application of Vanadium based SCR systems in HDVs. Keeping the exhaust temperature below 550°C should be possible for HDV applications. Some demonstrators use electrically heated catalysts (E-cat) upstream of the cc SCR but no information on pre-heating of the catalysts before engine start was found. An interesting approach is the installation of a small E-cat downstream of the AdBlue dosing to support the conversion of the injected urea into NH_3 at temperatures below the typical current threshold of ca. 200°C.

Various technologies are reported in literature for the thermal management of the exhaust aftertreatment system. Engine related options to increase the exhaust gas temperature are: throttling of intake and of the exhaust mass flow, multiple and late fuel injection, bypassing the EGR cooler and cylinder deactivation. Cylinder deactivation increases the exhaust gas temperature and engine efficiency significantly in low load driving and is a very attractive technology for thermal management in hot low load driving, and for DeSox of cc SCR systems. Since the exhaust mass flow is reduced, the exhaust gas energy (enthalpy) flow is not increased when cylinders are deactivated, thus the potential to support fast heat-up after cold start is limited. Finally, E-catalysts are also reported in literature and can increase exhaust gas temperature significantly. Overall, it is not decisive for the pollutant emission levels, how the energy is provided for fast heat-up and to maintain catalysts at sufficient temperatures in low load and idling. To combine and optimise the best combinations in terms of meeting the emission limits, good durability and fuel efficiency is a target for research and development towards EURO 7 HDVs.

We defined HD1 as best performing current technology (without close-coupled catalysts) as the basis for comparison with the more advanced EURO 7 technologies. The HD0 technology is needed as the basis to assess the emission reduction rates achievable by the advanced EURO 7 scenarios for the impact assessment.

The “HD2/HL2/HC2” technologies cover the relevant fuel options, i.e. diesel, CNG in stoichiometric SI-engines and CI engines using dual fuel diesel/NG combustion. The diesel HD2 technology comprises the best performing systems in the literature which are also in line with the demonstrator HDVs where test data was provided to us. The NG technologies were analysed to assess impacts of CH_4 as a fuel on the exhaust emissions.

The HD3 technology is to be understood as an analysis of the emission reduction potential by pre-heating the aftertreatment system to reduce cold start related emissions.

The HD4 technology was analysed by simulating the HD3 engine and aftertreatment technology in a hybrid HDV to assess if further significant pollutant reductions could be achieved by hybridisation.

Table 8-1 summarises the combinations of engine and Exhaust Emission control System (EATS) systems analysed for the possible limits per technology. A description of the technologies is provided below the table.

Table 8-1: Overview of technologies considered in the limit scenarios

Technology scenario		Description
HD0	Average EU VI D	With or without EGR, DOC, DPF and SCR in EATS box
HD1	Best NOx performing EURO VI D	Good thermal management, EGR, DOC, DPF and SCR in EATS box in underfloor layout
HD2	Optimised diesel with cc EATS and EATS box	Close-coupled DOC & deNOx+ASC + twin AdBlue dosing, EATS/engine volume ca. 6.5/1. Engines with hot and cold EGR, low raw NOx

Technology scenario		Description
		during cold starts (<2g/kWh), optimised thermal management, improved turbo-charging, fuel-injection.
HD3	Optimised diesel with pre-heated cc EATS	As HD 2 + pre-heating with diesel burner (5 minutes at 60kW for 330kW engine)
HL2	Optimised LNG/diesel engine	LNG CI engine with diesel ignition injection; emission control technology similar to HD2
HC2	Optimised SI CNG engine	Stoichiometric CNG engine with additional close-coupled TWC and OPF, optimised Lambda control, low lube oil losses.
HD4	Optimised diesel full hybrid with cc SCR and preheating of EATS	As HD3 + full hybrid (optional electric preheating instead of diesel burner)

The most important characteristics of the main technologies are explained in short below.

The main EATS components and the layout for diesel HD2 are shown in Figure 8-1. The close-coupled DOC supports CO, HC and H_2 oxidation to CO_2 and H_2O and consequently also provides heat to the SCR downstream from these exothermic reactions. Furthermore, the DOC increases the NO_2/NO ratio which leads to better low temperature NOx conversion in the close-coupled SCR. The “LT-SCR” is an SCR optimised for high conversion at low temperatures followed by an ASC to prevent NH_3 slip to the underfloor EATS since NH_3 can react to N_2O and NO_x on Platinum and Palladium coated catalysts. The HCI (hydro-carbon injection) is used to dose diesel into the exhaust to heat the DOC+DPF system in case an active regeneration is needed which is also used to desulphurise the underfloor SCR. For the DPF an improved filter substrate and/or a pre-loading with ash was assumed to reduce the drop in filtration efficiency after active or passive DPF regeneration. The underfloor SCR and ASC catalysts convert the remaining NO_x and NH_3 under hot driving conditions. Twin AdBlue dosing is assumed for individual NH_3 level control in both SCR catalysts, which allows e.g., to accomodate the different temperature levels. The control of the set of catalysts is supported by two NOx sensors, one PM sensor and several temperature sensors.

The HL2 LNG and the HD3 and HD4 technologies use the same EATS system: the HD3 and the HD4 technologies have a fuel burner with dosing and supply air blower or an E-cat with high electric power upstream of the close-coupled EATS system. The diesel burner as well as the high-voltage E-cat are not yet sufficiently developed for serial application according to the discussions in meetings with industry and the Commission, and we thus see a considerable risk that limits aligned with these technologies could not be met by the entire new HDV fleet in around 5 years from now.

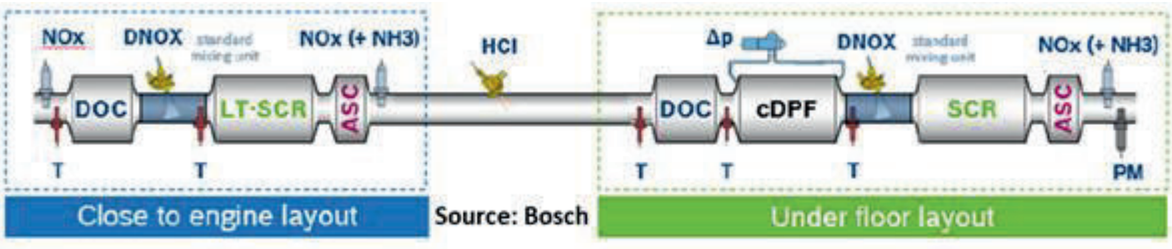

Figure 8-1: Scheme of the HD2 EATS system based on (Bosch, 2020)

For the EATS of the stoichiometric Otto engine a close-coupled TWC and an Gasoline Particle Filter (GPF), possibly combined in a 4WC (coated OPF) in addition to the current underfloor TWC have been assumed. For the OPF a filtration rate of ca. 95% was assumed to meet the PN limit scenarios. This assumption was taken from the corresponding LDV analysis. However, OPFs for CNG HD engines with such filtration rates have not been found in literature and were also not reported in the stakeholder meetings by any manufacturer. Thus, for the HC2 technology the PN limits include some risk that they might not be achievable in the near future. Since a reduction of lube oil consumption seems to lead to significantly lower engine out PN emissions, we are optimistic that overall a combination of improved OPF and engine technology can meet the limits recommended later in this report.

The EATS systems are supported in all EURO 7 technologies by advanced thermal management by the engine systems. For fast heat-up several technologies exist which were listed already before. The EURO 7 technology scenarios may adopt different combinations of these options depending on the R&D results towards EURO 7 and also depending on the different mission profiles of the HDV groups. Well known options are: bypassing the EGR cooler, multiple and late fuel injections (late ignition for CNG Otto), an exhaust gas flap to increase the work for charge exchange and intake air throttling. In general, improved insulation of the exhaust pipe and catalysts helps for faster heating and slower cooling rates.

For maintaining the EATS temperature in low load driving, cylinder deactivation is an attractive technology since it increases both the exhaust gas temperature and the fuel efficiency. Since the exhaust gas mass flow is reduced and the brake mean effective pressure per active cylinder is increased by cylinder deactivation, the overall energy flow in the exhaust gas is slightly lower than without cylinder deactivation. Thus, this technology is not sufficient for accelerating the heat-up of the EATs. However, for reasons of fuel efficiency improvement and efficient thermal management in low load and idling conditions, we expect cylinder deactivation to be part of the EURO 7 technology portfolio.

As an alternative or as a complement to active thermal management by the engines, electric heating (E-cat) is also an option.

Several mixes of the technologies listed above can be applied in the future to provide the energy and exhaust temperature for fast heat-up and for preventing cool-down of the EATS needed to meet the EURO 7 H2 and H3 scenarios. As mentioned before, the most suitable technology may vary according to the HDV category, mission profiles and numbers of engines produced per model.

Most technologies necessary for improved thermal management of the EATS reduce the fuel efficiency of the engine. Thus EURO 7 engines will use different engine operation modes for heat-up, maintaining EATS temperature and for hot EATS to achieve overall the lowest fuel penalty. The low NOx raw exhaust emissions at cold EATS will need high EGR rates and multiple late fuel injection. High injection pressure with small nozzle diameter and further improvements in the gas exchange and design of the combustion chamber are needed to keep particle, CO, and HC engine-out emissions low.

Such adaptive engine control strategies are necessary to achieve attractive fuel efficiency values for the customers together with very low pollutant emission levels. Thus, such strategies should not be illegal in EURO 7. Consequently, the emission limit scheme has to ensure that the combustion strategies applied in different driving conditions do not lead to high emission levels in relevant traffic situations.

Beside the energy demand for thermal management several target conflicts also exist:

- High NO_x conversion in SCR catalysts also increases the N_2O emissions. SCR systems with good low temperature conversion (e.g. Cu-Zeolith) produce N_2O as by product during heat-up and at high temperatures, which is an issue for the close-coupled system to meet lowest N_2O and NOx in parallel. Vanadium based SCR need higher temperatures for NOx conversion but have low N_2O up to ca 300°C, above this temperature Vanadium based SCR also produce high N_2O emissions. SCR systems without N_2O as by product have not been identified in this work.

- High NO_x conversions at high temperature (high load, DPF regeneration) also need high NH_3 dosing and filling level of the SCR. Due to the low storage capacity of NH_3 at high temperatures, the risk of NH_3 slip increases with increased NO_x conversion demand. With temperatures above ca. 400°C increasing fractions of NH_3 are oxidised and are not available for NOx conversion. Thus, increased NH_3/NO_x ratios need to be dosed at high load to maintain NOx conversion efficiency.
- At the SI engines (CNG), the TWCs convert NO_x, CO and HC with high efficiency after light-off. The lambda control area for best NOx conversion however is at slightly lower lambda then the area for best CO conversion. Thus, a NO_x/CO trade-off exists in setting the lambda window for the controllers.

8.2 Functional form of emission limits

The main aims for test and limit regimes are:

- Comprehensive coverage of all relevant driving conditions for RDE testing of all HDVs including
- urban delivery and bus (ca. 55km corresponding to ca. 3 x WHTC, shorter if re-starts included) up to
- long haul and coaches (ca. 230 km, ~ 11 x WHTC).
- Coverage of engine tests (WHTC, WHSC, FCMC) and VTP-on-road test with less than 120-minute duration to cover the demands from the CO_2 certification (Reg. 2017/2400)
- Similar requirements as for the LDV recommendation (comparability of requirements for N1-III and small HDVs)
- Limits to be attainable with defined technology packages in the defined test conditions

Relevant driving conditions with significantly different [g/kWh] emission levels are:

1. Cold start vs. hot conditions
2. Low load (< ca. 10% Prated (rated power)) vs. normal and high load
3. DPF regeneration vs. normal driving.

8.3 Coverage of On-Road tests

We have analysed the following basic options for limits regimes for on-road HDV tests for ISC, MaS and possible COP applications:

1. One limit for all
2. Different limits for hot and cold
3. Different limits for hot and cold and for low load
4. As above + separate handling in case of DPF regeneration

The complexity of the limit regime increases while the different driving situations are covered with more appropriate limits from 1) to 4). If e.g., one common NOx limit is set for cold starts and for hot driving conditions, either the limits cannot be met by the technologies in worst-case cold start conditions and/or the limits are much higher than the NOx levels achievable in hot driving conditions.

Since a high share of HDV kilometres is driven in long haul operation (Table 8-2), a proper limitation of hot driving is important for the overall NOx emissions. Since hot emissions of NOx, CO and HC is expected to be at a very low level in normal conditions for EURO 7 compliant HDVs, the share of cold start extra emissions on the total HDV emissions will increase in future. Since starts of HDVs often happen in urban areas, the health effects of lowering cold start extra emissions may be proportionally higher than a reduction of hot emissions. Consequently, EURO 7 must ensure a reduction in cold start and hot running emissions.

Table 8-2: Assessment of the share of long-haul trips in the total mileage of new registered HDVs in Europe (data from an ongoing project for DG CLIMA)

Vehicle category	Total annual mileage	Of which long haul kilometres
	[Million km]	%
Coaches (HF buses)	974	71%
City buses (LF buses)	705	0%
Long haul (tractor)	16 256	97%
Regional delivery	4 624	70%
Urban delivery	309	10%
Construction	1 672	5%
Others (Municipal+Offroad)	185	3%
	24 727	**75%**

To provide a broad basis for possible selections of limit combinations, we elaborated a limit regime supporting the aforementioned option 4), i.e., a separate limitation of cold/hot/low-load and DPF regeneration events. Possible simplifications are discussed in chapter 8.4.

Figure 8-2 shows the basic correlations between instantaneous emissions [g/s], the cumulated emissions in a test [g] and the engine work-based emissions in [g/kWh]. A similar trend occurs for all exhaust gas components reduced in catalytic converters (NOx, CO, HC). After warm-up of the EATS, the instantaneous emissions drop by more than one order of magnitude. Consequently, the cumulated emissions in a test rise with a high gradient after cold start, after EATS warm-up the gradient drops significantly. The gradient of the cumulated emissions in the graph represents the g/kWh, i.e., the change of emissions [g] per engine work delivered [kWh]. When emissions do not increase much during hot driving, the engine work-based emissions [g/kWh] drop with increasing test length since a similar emission value [g] is divided by an increasing engine work [kWh]. This effect will be even more pronounced in EURO 7 technologies, since hot emissions can be close to zero in most hot situations due to the extended catalyst volumes, while still some cold start extra emissions will remain, even with optimised warm-up strategies. Finally, the orange line shows the moving average of the "hot mg/kWh", which is built here from instantaneous emissions after 1xWHTC work is finished. A short phase of higher emissions is visible due to a warm start after 10 minutes soaking after the 1st WHTC is finished, then the hot emission level of the best performing EURO VI D truck remained very low. The [mg/kWh] level including the 1st WHTC with cold start (red dotted line) approaches the hot emission level asymptotically with increasing test length.

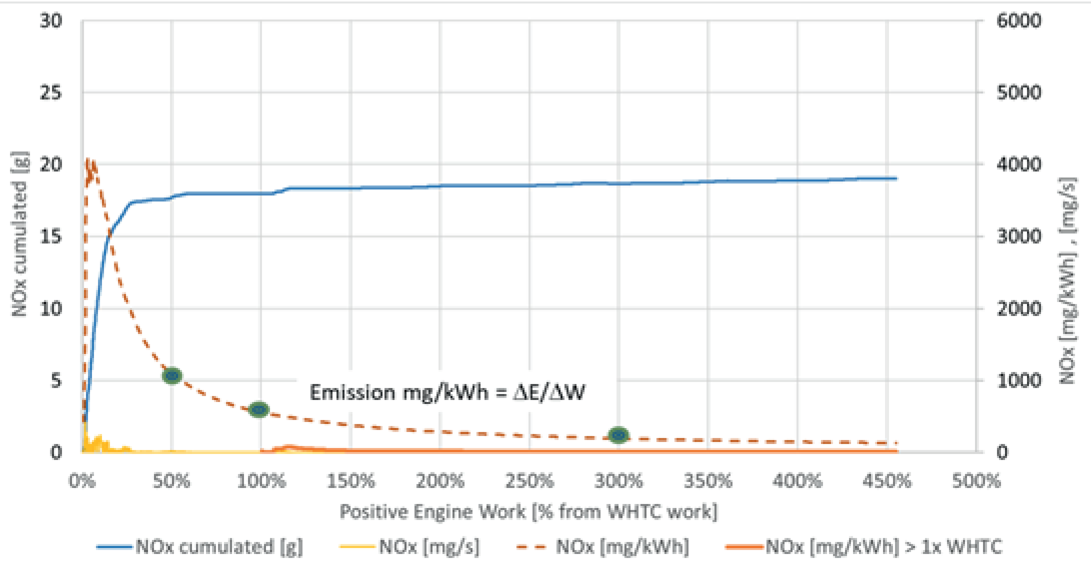

Figure 8-2: NOx emissions of the best performing EURO VI D truck (300 kW diesel engine) in consecutive WHVC test after 20°C cold start

For a proper control of the hot emission levels the limit values [g/kWh] should be rather low, i.e., a level aligned with longer minimum test distances. A minimum distance that is too long would however not allow to include the CO_2-VTP test. The typical average driving distances of urban HDVs of ca. 55 km correspond for average vehicles on a flat road to ca three times the WHTC engine work. The distance needed to cover this work varies heavily with vehicle loading, vehicle category and road gradients. Thus, we suggest defining the minimum test distance via the cumulated positive engine work and not via a minimum test distance. If the limit is properly aligned to the minimum test distance, all shorter trips are implicitly covered by such a limit regime, since high emissions before reaching the minimum distance cannot be compensated any further and would lead to a limit exceedance. Since the vehicle cannot know how long a trip may be, the emission control system must always ensure compliance with a possible test from engine start on.

However, we suggest using different limits for hot and for cold driving conditions, since this option allows lower levels for the hot driving conditions compared to a single limit. The corresponding limit regime is designed as follows:

- The cold phase and the beginning of hot conditions are limited by a “budget”, which defines the maximum emissions allowed for a test up to an engine work of 3 times the WHTC. This budget is defined by a corresponding limit $[mg/kWh]_{Budget}$ and the kWh work the tested engine delivers in 3xWHTC. Any test up to 3xWHTC work must be below the resulting limit in [mg/test].
- The hot emissions are limited by a separate $[mg/kWh]_{hot}$ limit, which must be met under hot conditions.
    - Based on a proposal from JRC, the hot limit was introduced for a 90th percentile of all moving average windows (MAWs) in the presentations in the AGVES meetings on 08.04.2021 and 27.04.2021. To ensure that only hot driving conditions are included in the 90th percentiles, the first hot MAW is

built 10 minutes after engine start. The "90th percentile[25]" limit values presented in chapter 8.4 refer to this option.
  - An alternative is to start building the hot MAWs after 1xWHTC work is finished. In this option the limit may be applied to all hot MAWs (100% limit) and not only to the lowest 90% ("90th percentile") of the MAWs[26]. The "90th percentile" limits could be multiplied by a factor of 1.3[27] to convert them into "100th percentile limits" for the hot MAWs.

- To safeguard the MAWs not covered by the possible 90th percentile approach, a "100th percentile" limit was added, which must not be exceeded in any MAW between first and last second of a test.

Overall, the base limit scheme presented in AGVES in April 2021 leads to a set of 3 limit values, which are also illustrated in Figure 8-3:

1. "Budget" for all tests below 3 x WHTC work
2. "100th Percentile" for all MAWs between first and last second of the test
3. "90th Percentile" for all MAWs starting 10 minutes after the engine was started in the test.

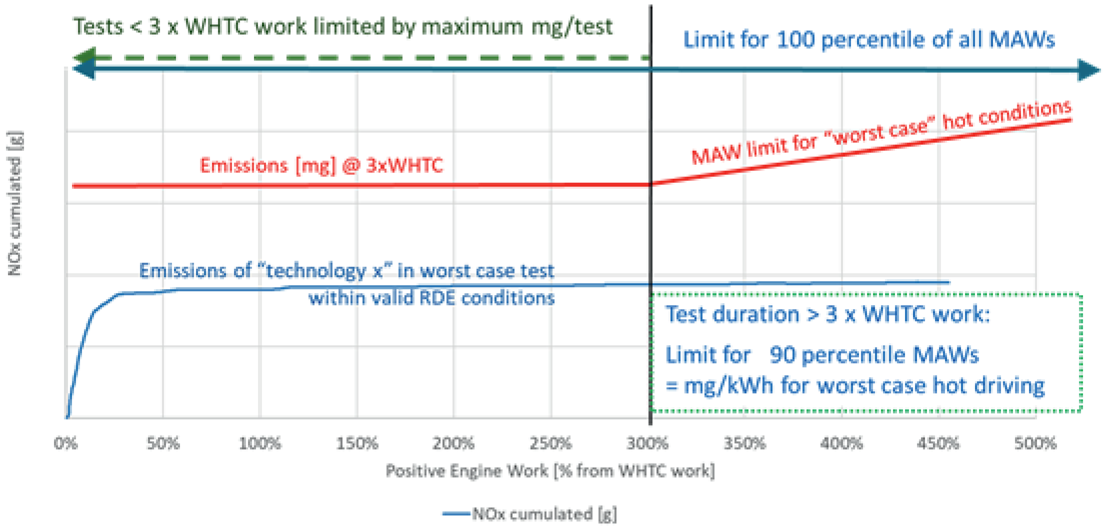

Figure 8-3: Scheme of the possible emission limit regime for EURO 7 HDV RDE testing

Under worst-case test conditions, the emissions of a "worst-case cold start with 1 x WHTC" work followed by "2xWHTC work under worst-case hot driving conditions" should lead to the worst-case test result for 3xWHTC work. Thus, the three limits discussed above can be linked to each other, so that one limit could be calculated from the other two (Equation 8-1).

Equation 8-1	$[mg/kWh]_{3xWHTC} = ([mg/kWh]_{1x\ WHTC\text{-}cold} + 2 \times [mg/kWh]_{hot}) / 3$

As explained before, the hot emissions are limited by a 90th percentile of MAWs and the 100th Percentile limit is applicable over the entire test not only limiting the cold start phase (e.g., for NH_3 highest emissions are expected under hot and high load conditions).

[25] The MAWs are built similar to the current EURO VI regulation, where each second a new MAW is started, which each have the length of the work delivered in one WHTC. The integrated emissions in a MAW [g] are divided by the MAW work [kWh] to calculate the [g/kWh].

[26] After 1 WHTC work all HD engines and the EATS have to be hot, while after 10 minutes still MAWs may include emission events influenced by cold start, which would be excluded by the 90th percentile rule.

[27] The emission level of the lowest 90th percent of a sample of MAWs in a test are lower than the highest MAW (100th percentile). An analysis of MAW distributions of EURO VI tests showed a typical ratio of 1.3 between the 100th and the 90th percentile (see chapter 5). This factor heavily depends on the test route and test conditions. However, converting the 90th percentile hot emission limits with this factor to 100th percentile limits would lead to limit values we consider to be achievable by the technologies in all hot MAWs.

Furthermore, the probability of having a combination of all possible worst-case conditions (driver, route, weather, vehicle behaviour) in a time slot over 1xWHTC is higher that the probability of such a mix in a test over 3xWHTC.

Thus, Equation 8-1 is not exactly applicable for the three limits discussed before, but the limit values should approximately fulfil this relationship. Since the elaboration of possible limits started with limits for the budget and for hot driving conditions, base values for the 100^{th} percentile limits are based on this relationship with some adaptations for taking higher worst-case probabilities for the 100^{th} percentile into consideration.

Equation 8-2	$[mg/kWh]_{100Perc.} = 3 \times [mg/kWh]_{budget} - 2 \times [mg/kWh]_{90Perc.})$[28]	*Based on* Equation 8- 1

Possible simplifications

Since the three limits are linked, one may omit one of these without significantly reducing the coverage of tests. A suitable simplification is the following combination:

- "Budget" for the test phase up to 1 x WHTC work (i.e. the 100^{th} percentile value, which remains also as a cap for all MAWs over the test)
- Hot limit for the entire test phase starting after completion of 1xWHTC work and lasting to the end of the test (using the 90^{th} percentile as limit value, but multiplied with the factor 1.3 to convert the 90^{th} percentile to 100^{th} percentile).This "1xWHTC work budget" is not compatible with the 90^{th} percentile rule, since the application of the percentiles needs a sufficiently high number of MAWs and thus a minimum test length of more than ca. 3 x WHTC work. Thus, the test distance between 1 x WHTC and 3 x WHTC would not be covered.
- Limiting the emissions over the entire test instead of the MAWs would further simplify the limit regime and would lead to a very similar approach as recommended for LDVs. In this option, the emission control in long trips would be less demanding compared to a $100^{th}/90^{th}$ percentile method for hot MAWs in worst-case test conditions. Due to the low hot emission limits this risk is limited. Which of these (quite similar) methods is most suitable for all conditions is not yet clear[29].

Coverage of short tests

With the "budget" method any short test can be evaluated. This option can be introduced by adding only a few lines into current limit regimes.

Emissions are evaluated as in EURO VI:

Equation 8- 3	$\text{Emissions [g/kWh]} = \frac{\text{Emissions [g]}}{W_{pos}}$	***Same as in EURO VI***

With the positive work being the cumulated positive engine work over the test, which can be calculated also using the average positive engine power and the test time:

[28] As described before, the limit value for a 100^{th} percentile should be set ca. 30% higher than the limit for a 90^{th} percentile. Here this conversion factor was not applied, which results in a slightly higher value for the 100^{th} percentile to take the additional risk related to shorter tests into consideration.

[29] Since the 90^{th} percentile and MAW approach was recommended by JRC rather late in the project, all pros and cons are yet not fully analysed. Tests on PHEVs may need special definitions to achieve fair conditions compared to conventional HDVs due to possible ICE engine starts at any time in a test. How PHEV test provisions can be matched with 90^{th} percentile MAWs is yet not analysed.

Equation 8-4	W_{pos} = Pos. Work [kWh] = $\bar{P}_{pos}$ x t_{test}	***Same as in EURO VI***

As add on we introduce the "Reference Work" $W_{pos\text{-}R}$:

Equation 8- 5	If W_{pos} < 3 x W_{WHTC} → W_{pos} = $W_{pos\text{-}R}$ = 3 x W_{WHTC}	***New element***

Using $W_{pos\text{-}R}$ in Equation 8-3**,** the measured emissions would be adjusted in case of tests shorter than 3xWHTC work. As an alternative with exactly the same effect, Equation 8-3 can be transformed to calculate the Emission limit in [mg/test]:

Equation 8- 6	Emissions [g/test] = $W_{pos\text{-}R}$ x [g/kWh]$_{budget\text{-}limit}$	***Alternative to adjusting the test results using $W_{pos\text{-}R}$ in Equation 8-3***

Coverage of low load tests

To include also low load tests in the emission limit regime, one more equation can be added to the current evaluation method by introducing the "Reference Power, $\bar{P}_{pos-R}$:

Equation 8- 7	If $\bar{P}_{pos}$ < 10% of P_{rated} → $\bar{P}_{pos}$ = $\bar{P}_{pos-R}$ = 0.1 x P_{rated}	***New element***

$\bar{P}_{pos-R}$ is thus replacing $\bar{P}_{pos}$ in case of low load tests or low load MAWs for the calculation of W_{pos} in Equation 8-4. As mentioned before, the corrected W_{pos} value can be used to correct the test result [mg/kWh] or to calculate the emission limit per test. For the reference power we suggest correcting the test result in [mg/kWh] with the corrected work since this method is applicable for short tests (budget) as well as for long tests (MAWs).

In any case first the real work shall be calculated to fix the MAW and/or the total test work, then the correction shall be applied to calculate corrected test results or correlated limits but then no further adjustment of the MAWs or total test work is foreseen. The correction thus is applied only to the emission result or limits.

With Equation 8-7 emissions of low load tests are limited by the absolute value[30] which corresponds to a test with an average positive power of 10% of the rated power. Analysis of test data and simulation results indicate that driving with average 3% of rated power (e.g., extreme stop-and-go) can be managed with approximately the same emissions per test as a trip with 10% of the rated power (e.g., dense urban traffic). Consequently, the test result corrected with the Reference Power approach of low load cycles is similar to a result driven with 10% of rated power on average. Figure 8-4 shows the results for chassis dyno tests with the best performing EURO VI D truck evaluated once with and without the reference power method. It has to be noted that this truck engaged permanent exhaust gas heating in the stop-and-go test and had by far the lowest NOx of all EURO VI trucks analysed in stop-and-go cycles.

[30] The absolute values represent [g/test] and/or [g/MAW]

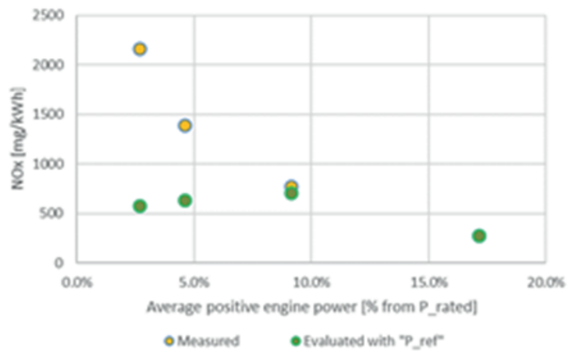

Figure 8-4: NOx emissions measured at the best performing EURO VI D truck in WHVC and stop-and-go conditions (all tests evaluated for 1 hour duration) with and without application of the reference Power method

The reference power method seems to be a simple extension of existing test evaluation methods to include low load tests in the on-road test regime.

Coverage of long idling tests

By applying the "Reference Power" method together with the "Budget" limits for short tests (<3xWHTC work), also long idling tests are covered with reasonable emission limits. For idling tests, the power is simply set to 10% of the rated power and multiplied with the limit value of the budget (equation 8-8).

Equation 8-8	$\text{Limit [g/h]} = \text{Limit}_{\text{Budget}}\ \text{[g/kWh]} * P_{\text{rated}} * 0.1$

Using equation 8-8 for example for the limit values elaborated for the HD 2 diesel technology shown below in Table 8-9, leads to the idling limits in Table 8-3. These values need active thermal management during idling to keep DOC and SCR in the operating temperature. A fuel-efficient technology for meeting this target is cylinder deactivation, which is currently in serial production only at LDVs but should also be applicable to HDVs during idling (e.g., Sharp, 2021).

Table 8-3: Example for idling emission limits resulting from the recommended approach and the limit values from Table 8-9 for the HD 2 technology with a 330 kW rated power HD engine in [g/h]

g/h	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O	CH_4
HD 2	4.95	6.6×10^{12}	0.33	41	2.48	2.15	4.6	1.0

Current idling emission limits in US are 30g NOx/h. From model year 2024 CARB proposes 10 g/h and for model years from 2027 on 5 g/h, which are seen to be feasible (CARB, 2020).

To incentivise engine stops during vehicle standstill, we suggest handling vehicle standstill with engine stop and idling identically in all evaluation steps. During engine stop times thus test time relevant for the reference power correction would be accumulated as during idling but no emissions would be added. "Idle" may thus be defined either as vehicle standstill or engine power below 2% of rated power.

While long idling is covered by the budget-limit values and may be performed as isolated idling test, shorter idling phases do not need specific provisions as long as the reference power method is applied in all test areas (budget, hot and 100th percentile limit) and the share of idling is not excessively long.

A critical test would be a multiple alteration of long idling followed by high load driving, since such a mix could lead to average power values above 10% from rated power and thus the idling time adds only emissions and not work to the [g/kWh] result. Furthermore, during long idling the underfloor catalyst cools down since the close-coupled catalyst is sufficient to convert the low exhaust volume flows in idling. Thus, several semi-cold starts under worst-case conditions could be summed up in the budget area (<3xWHTC) and also in the hot phase (90^{th} percentile range). To overcome this issue, we suggest limiting both the share of idling and the maximum continuous idling time in the normal RDE driving test (e.g., 25% share and maximum 60 minutes continuous idling or engine stop would cover normal use, see chapter 6). In case of longer continuous idling before a driving phase, a new test evaluation should be started beginning with the corresponding idling phase (or driving phase) to allow the budget limit for the following semi-cold test period. Thus, long idling can be started at any time in a vehicle test but would be evaluated as a separate test if followed by a driving event.

This seems to be a simple option to define a mix of long and short idling with driving phases as valid tests, and thus to cover all possible driving conditions also under any special urban distribution conditions.

Calculation of the positive engine work in the WHTC

Another recommended extension of the current test evaluation methods is a simplified way to calculate the positive engine work delivered during a single WHTC. For third-parties this value is sometimes difficult to obtain and can be replaced by a simple approximation assuming the average positive engine power in a WHTC to be 22% of the rated power. With this simplification we get for the 0.5 hour WHTC test duration:

Equation 8- 9	1 x WHTC-work [kWh] = 0.11 x P_{rated}	**New element, based on =** **W = 22% x P_{rated} x 0.5h**

with 0.11…..conversion factor [kWh/kW] in WHTC

With this approach all evaluation methods need as input only the rated engine power, the measured instantaneous emission signal, and the instantaneous engine power signal (torque and rpm respectively).

DPF Regeneration

DPF regeneration events should be included in the EURO 7 test regime. Since the suggested approach to setting emission limits is quite ambitious, the resulting limits would be unlikely to be possible to meet during a test with DPF regeneration31. This is especially the case for PN, but other exhaust gas pollutant emission levels also increase during regeneration.

Typical DPF regeneration intervals at current HDVs are above 1000 km and take ca. 30 to 60 minutes i.e., typically not more than one WHTC work distance.

Consequently, we suggest the following method to limit the extra emissions during DPF regeneration according to the regeneration frequency of the DPF in the tested vehicle. The method is only applicable if a DPF regeneration occurs during a test, including tests with DPF regeneration is not mandatory for a valid result.

[31] While PN emissions can be lower than 1E+11/kWh in normal driving, the levels during DPF regeneration can hardly be lower than 1E+12/kWh during a 3xWHTC work test distance.

- The number of DPF regenerations must be integrated and stored in the OBD memory together with the total operation time. From this data the average time between DPF regenerations is available. Correct recording of DPF regeneration can be checked in tests when DPF regeneration occurs.

Proposal for the evaluation, if regeneration occurs during a test:

- The DPF regeneration should be finished in the test and minimum 20 km further distance shall be driven after the end of regeneration. The accountable regeneration time is limited, e.g., with max. 60 minutes or 1xWHTC.
- A second test shall be driven.
- The test results for all exhaust gas components shall be weighted according to the average time between regenerations. Weighting by time shares is preferred since DPF regeneration will occur more frequently in HDVs running in low load/low speed missions, where the distance is not the relevant criterion.

The expected distance until next active regeneration may be announced by the vehicle (e.g., via TCI system), to allow 3rd party test labs to better decide if DPF regenerations may occur within the available test time.

Applicability to hybrid power trains

The test methods described should also be applicable to HEVs and PHEVs, but an ideal configuration was not analysed in this project due to a rather late inclusion of this evaluation approach in the analysis.

In general, the positive engine power (P_{pos}) for hybrid vehicles can be defined as the sum of engine and E-motor power delivered to the driven axle(s), i.e., the work to drive the vehicle, counted if the sum of both values is positive. In this case the brake energy recuperated adds positive work to W_{pos} and thus reduces the test result in [mg/kWh] compared to the option when only the ICE power is considered.

This positive system work has to be provided by the HDV via OBD connection. The signals for the ICE torque and speed are already standardized in EURO VI. These values can be verified easily in the VTP tests prescribed for the on-road CO_2-verification[32] since in the VTP test the power at the driven wheels is measured via torque meter wheel rims and the loss maps of all transmission systems are available for the vehicles from component certification according to regulation (EU) 2017/2400. Since the VECTO tool is already applied for the VTP evaluation, a check of the system power as well as of the engine torque and speed data provided by the OBD connection could be added to the VTP evaluation.

For specific test conditions of HDVs with large rechargeable energy storage systems (RESS, e.g., battery), the evaluation option using the work delivered to drive the vehicle can cause disadvantages, namely if electric energy is produced on-board via the electric motor using energy from the ICE. This could happen e.g., in low load driving (ICE load shift towards a point with better engine efficiency) or in case of Geo-Fencing, when the battery state of charge is low before entering a zero-emission zone.

In these cases, the ICE may deliver in total much more work than used for driving the vehicle over an entire test or at least within single MAWs. If only the work used for driving the vehicle is counted as W_{pos} in the [mg/kWh] result, this would result in an artificially high test result.

Due to a poor energy efficiency of on-board battery loading by ICE in many driving conditions, it may not be necessary to find a specific solution for such a test case.

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[32] Defined in in Regulation EU 2019/318 as amendment to regulation 2017/2400.

Consequently, PHEV HDVs may not offer the option for on-board battery charging. A rather simple solution would be to include the State Of Charge (SOC) of the battery into the test evaluation by converting the change of energy stored in the battery (ΔSOC) into related ICE work (kWh). This could be done by using a simple conversion factor assuming e.g., 75% overall efficiency from mechanical ICE power output to electric power accumulated in the battery cells. The generic conversion factor could be adjusted in the future using the HDV CO_2 monitoring data as soon as hybrid vehicles are included in Regulation 2017/2400.

8.3.1 Coverage of Engine Tests

The following engine tests are demanded for the HD CO_2-regulation (Regulations EU 2017/2400 and 2019/318):

- WHTC cold started at 20°C
- WHTC hot start (after cold WHTC and 10-minute soak time)
- WHSC after a hot preconditioning phase (as a COP option for CO_2-certification of engines)
- Fuel Consumption Mapping Cycle (FCMC) after a hot preconditioning phase

In EURO VI the weighted result of WHTC cold (14%) + hot (86%) is limited for pollutants. The limits also have to be met in engine CO_2 certification. Certainly, these tests shall also be well covered by the EURO 7 limits to avoid any cycle optimisation for low fuel consumption at cost of high pollutant emissions.

The emission limits for the engine tests can be streamlined with the test methods and limits for on-board tests with the following test and evaluation conditions.

WHTC

Since the first WHTC is started cold at 20°C and the second WHTC has a hot start with 10 minutes soak time after cold WHTC, the 100-percentile limit and the “hot limit” are applicable. A conversion from a 90-percentile limit to a 100-percentile for the hot WHTC does not seem absolutely necessary. Since the WHTC is not a worst-case test and since the type approval engine will rather not be a worst-case out of the serial production spread, the factor 1.3 for conversion of 90^{th}- to 100^{th}-percentile is levelled out by these simpler test conditions.

Suggested limits:

- 100^{th}-percentile (cold) limit for first WHTC
- 90^{th}-percentile (hot limit) for the second hot WHTC.

FCMC

The FCMC is started after a hot preconditioning phase and tests ca. 95 steady state points in the engine map as basis for the CO_2 simulations in the VECTO tool. Each steady state point is held 45 seconds where the last 30 seconds are used as measurement value, then a ramp to the next test point is driven (Figure 8-5). In the current regulation, the pollutant emissions of the test points must meet the NTE regulations of EURO VI.

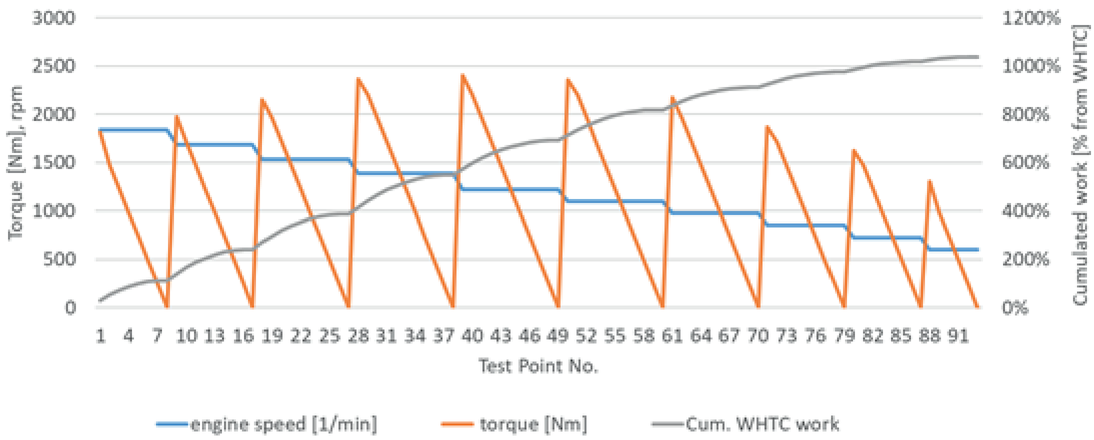


Figure 8-5: Test points and cumulated engine work in the FCMC for a EURO VI 340 kW HD engine

Since the FCMC is a hot-start test, the hot emission limits shall be applicable. The FCMC lasts for ca. 11xWHTC work. Thus, the MAW method is applicable but setting the limits only for the 90th-percentile of MAWs would leave several map points controlled only by the rather high 100th-percentile limit. OEMs may use this freedom to optimise the test points which are most relevant for the VECTO CO_2 results.

A challenging feature of the FCMC are the engine load jumps from constant zero torque at a given engine speed to constant maximum torque at the next lower speed. Such manoeuvres will not occur in real driving at the low engine speed test points since such load changes from low to full load with parallel engine speed drop can occur on the road only after upshifts. In these low speed, high torque areas of the FCMC the exhaust gas temperatures are very high in the constant phases and the boost pressure is quite low after the ramp, which is very challenging for NH_3, N_2O, NOx and PN control. Special controlling of the emissions in these artificial ramps may bias the test results in the following constant phases, which are relevant for the CO_2 results.

For these reasons and since the pollutant tests in the FCMC only need to cover the relevant fuel map points, we suggest the ramps from zero to maximum torque are not included in the emission evaluation.

The recommendation for the FCMC test is therefore:

- Apply the 90th-percentile limit, converted with the 90th/100th percentile conversion factor of 1.3 to a 100th-percentile. The limit is then applicable for 100 percent of all MAWs in the FCMC. The time slots from the torque increases from zero to maximum load up to the first CO_2 measurement phase at the consecutive maximum torque test point shall not be included in the evaluation.

WHSC

As with the FCMC, the WHSC is started hot after pre-conditioning, so the hot emission limits are applicable. The WHSC also has load ramps from zero to maximum torque but only at engine speeds occurring also in real driving. The high loads and load steps however are also challenging especially for PN and NH_3. Since the limit applies as 100% limit and not as 90th-percentile limit for the WHSC, the application of the conversion factor from 90th- to 100th-percentile limits is reasonable for the WHSC[33]. Since the engine work in the WHSC is only ca. 120% of the WHTC work, building MAWs for the limits is not needed but the result for the entire test can be limited.

[33] As basis for a decision on the necessity of increasing the limits for the WHSC by the conversion factor, test data on a EURO 7 demonstrator engine in WHSC, WHTC and FCMC cycles would be helpful.

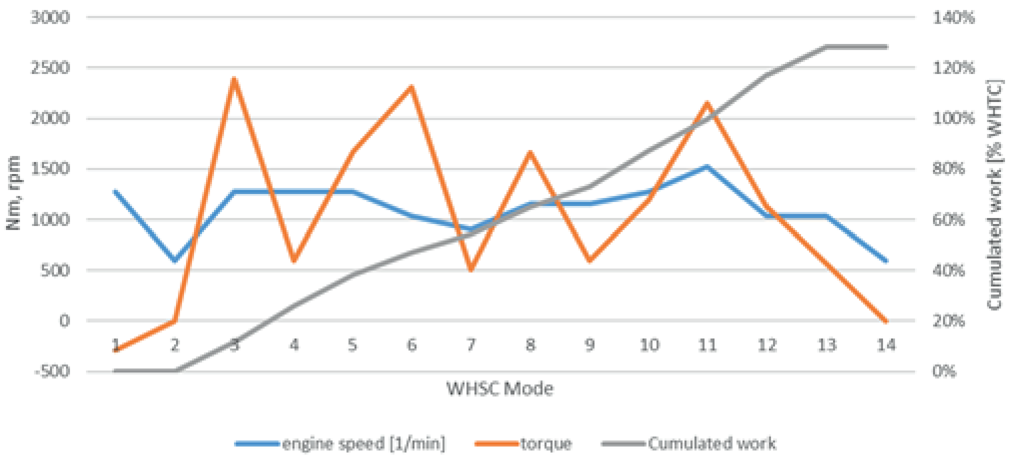


Figure 8-6: Test points and cumulated engine work in the WHSC for a EURO VI 340 kW HD engine

The recommendation for the WHSC test is therefore:

– Apply the 90^{th}-percentile limit, possibly converted with the $90^{th}/100^{th}$ percentile conversion factor of 1.3 to a 100^{th}-percentile. The limit is then applicable for the total WHSC test result, i.e., measured emission [g] divided by the total positive work delivered [kWh].

8.4 Recommended emission limits

We have assessed the possible emission limits

1. for the test conditions described in chapter 6.3
2. for the technologies described in 8.1
3. using the evaluation conditions described in chapter 5

based on the test data on the best performing EURO VI D truck, emission test data from literature on demonstrator engines using the mentioned EURO 7 diesel technology and test data provided by industry for a EURO 7 HD engine demonstrator and preliminary results from a EURO 7 HDV demonstrator.

The steps were as follows:

(1) Collection + analysis of EURO VI D HDV emission tests and selection of best performer for further processing.

(2) Collection and analysis of test data from literature and from the EURO 7 HD demonstrators.

(3) Definition of worst case test condition for cold and hot driving conditions within RDE boundaries. The worst-case was defined as a cold start at -7°C with highway uphill driving followed by a stop-and-go and dense urban driving situation followed by rural and motorway driving. It is likely that even more demanding conditions than the worst-case test condition may occur within normal driving. Furthermore, the worst-case condition will differ for variations of EURO 7 setups and for different exhaust gas components. To consider the high probability that the test conditions used in the simulations do not reflect the future worst-case conditions, we added a safety margin to the recommended limits to account for more challenging conditions.

(4) Simulation of the EURO 7 diesel technologies to close gaps in data:

a. Convert tests at different temperatures to -7°C
b. Convert tests at WHTC and other cycles to worst-case conditions
c. Convert PN_{23} test data to PN_{10} values
d. Assess cold start emission reduction by pre-heating
e. Convert emission levels to extended useful life

(5) Set up emission levels for the different technologies for the worst-case driving conditions (for cold start up to 1xWHTC, up to 3xWHTC and hot driving).

(6) Add "safety margin" for engineering target to get the final limit scenarios per technology. Note: assuming that all tests which are around the limit within the analyser tolerances are repeated with a reasonable statistical approach, no extra margin for analyser uncertainty is needed. Thus, this is not included in the recommended limit values.

(7) Lift limit values from (6) if they are below the expected analyser capabilities until they are at the analyser capability level.

As an example, Figure 8-7 shows the most relevant data and the main steps of this process for NOx, including trend lines for the best performing EURO VI D truck in WHVC and the conversion to a worst-case test at -7°C as well as simulations and test data on a demo HDE for EURO 7 HD2 technologies. For the HD2 technology the expected emission levels for an ISC or WHVC like test at 20°C are also plotted to illustrate the expected typical emissions under normal driving conditions. In an ISC test with 4xWHTC length and cold start at 23°C the HD2 truck would emit ca. 20mgNOx/kWh, in the worst-case RDE conditions 80mg/kWh are expected for the HD2 (55mg/kWh for HD3).

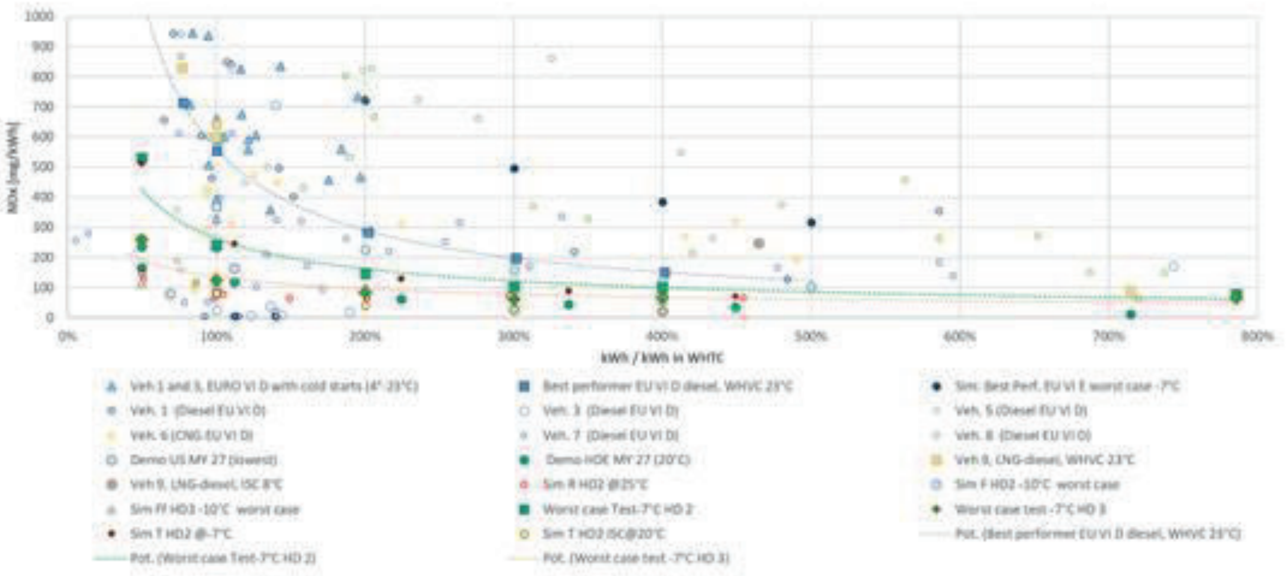


Figure 8-7: HDV NOx emissions from tests, data collection and simulation in various driving conditions (note: test data does not cover temperature below -3°C and worst-case driving conditions; many tests in the graph are hot started)

The analyser capabilities considered in step 7) are described in chapter 3; for completeness the results for HDV on-board tests are repeated in Table 8-4.

Table 8-4: Analyser capability limits expected for on-board tests in EURO 7 (see chapter 3)

	NOx	SPN_{10}	CO	NMOG	NH_3	N_2O	CH_4	HCHO
mg/kWh (#/kWh)	89	1.6×10^{10}	136	47	17	32	47	29

Assessment of related average real world emissions

The data from measurements and simulation used in the steps 1) to 5) is described in the HDV sections in "Task 1 Report Annexes; Techno-economic feasibility of new pollutant emission limits for motor vehicles".

Within the working steps listed above, beside the recommended limits, the expected average real world emission levels for the following driving situations were also elaborated:

- Current ISC test conditions with 1, 2, 3 and 4 x WHTC work length with cold start at 23°C
- Current ISC test conditions with 1, 2, 3 and 4 x WHTC work length with cold start at -7°C
- Worst-case test conditions with 1, 2, 3 and 4 x WHTC work length with cold start at 23°C
- Worst-case hot driving conditions.

The results for the ISC test conditions were used as the basis for setting up the HDV emission factors for the impact assessment, which is described in a separate report. From the expected emission limits under worst-case conditions, the limit values shown below were elaborated by adding a 50% margin to consider OEM development target needs. This is the typical approach needed for OEMs to consider the serial spread of components and the uncertainty if in-house tests fully reflect worst-case test conditions, which are not yet known. This approach is already applied today for engineering targets by manufacturers.

PN_{10} versus PN_{23} limits

An important assumption for setting the limits for PN_{10} was the conversion factor from PN_{23} to PN_{10} since most test data only included PN_{23}. We used a factor of 1.4 as a ratio between PN_{10} and PN_{23} which is a typical value for well performing diesel HDVs DPF from the H2020 project DownToTen (Landl, 2019) and from the tests performed in the current project using the DownToTen dilution system at TUG (see Appendix 2 to the Annex to this report for all test data). The EURO VI D truck tested in this project (vehicle H5) had on average a ratio of 1.5, covering tests from stop-and-go up to full loaded motorway driving. One motorway test had a ratio of 2.3 (Figure 8-8), though repetitions of this test gave a ratio of 1.6 suggesting it was an outlier. The EURO VI C truck (vehicle H4 in the Appendix) had on average a PN_{10}/PN_{23} ratio of 1.7.

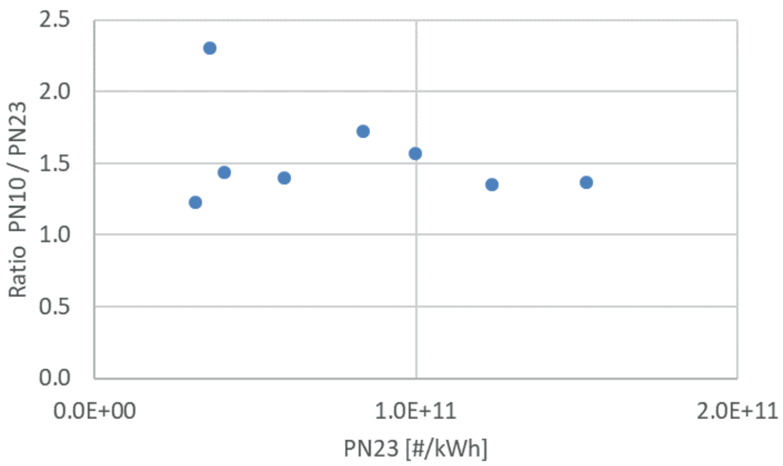


Figure 8-8: Ratio of PN_{10} to PN_{23} emissions plotted over the measured PN_{23} for vehicle H5 (EURO VI D truck)

It has to be noted that much higher ratios were also found (up to a factor of 2.5). We did not apply the worst-case principle here, assuming in future further improvements would be implemented. Such improvements could include: improved particle filter substrates with preloading of ash, smaller pore sizes, coating or other technologies for reducing PN emission increases during and after active or passive DPF regeneration combined with reduced lube oil losses and low ammonia slip and thus lower nitrate production. Furthermore, the PN_{10} measurement devices need to be designed to reliably eliminate all non-solid particles[34].

Future improved DPF technologies and PN measurement systems may prevent high PN_{10}/PN_{23} ratios but are not yet demonstrated by any demonstrator test data. Thus, we suggest to review this PN_{10}/PN_{23} ratio by measurements on demonstrator technologies (if made available) under worst-case test conditions in a next step. If a higher ratio of PN_{10}/PN_{23} is found, the limit values should be adjusted accordingly. In this review, the impacts of crankcase ventilation should also be considered, which should be included in EURO 7 PN limits[35]. For PN the higher uncertainty from measurement systems compared to gaseous components, especially in the low emission ranges recommended for EURO 7, also need to be considered, e.g. by sufficient test repetitions when results are in the range of the emission limits +/- the analyser uncertainties. This is especially relevant in case of third-party tests.

CH_4 and N_2O Limits

CH_4 and N_2O can contribute significantly to total GHG emissions from modern vehicles, and they also have health and environmental effects (see Chapter 3). For diesel engines mainly N_2O, for CNG SI engines mainly CH_4, contribute to the CO_2 equivalent (CO_2e) global warming potential (GWP) exhaust emissions. The contribution typically is between 2% and 10% of the CO_2 emissions. For LNG CI engines (HPDI) both N_2O and CH_4 emissions are relevant since unburnt fuel is emitted mainly as CH_4 and the EATS is similar as for diesel. In the diesel EATS N_2O is produced mainly as a by-product of NOx conversion in SCR systems and from NH_3 conversion in the ASCs. Since the efficiency of HPDI engines is almost as good as diesel engines, and because LNG has a lower carbon density than diesel

[34] Tests at TUG used a catalytic stripper combined with thermal treatment (DTT, 2020). Systems using evaporation tubes only seem not to be sufficiently efficient in removing non-solid particles in several relevant conditions, such as during DPF regeneration (Giechaskiel, 2019).

[35] PN emissions from crankcase ventilation are especially relevant in hot driving conditions. Ventilation shall either be fed into the exhaust gas line or emissions from ventilation need to be measured separately and added to the tailpipe emissions.

per MJ of fuel, HPDI engines have overall lower CO2e emissions than diesel and CNG SI engines but typically higher CO2e emissions from CH4 and N2O. Figure 8-8 compares results from such a HPDI engine with EURO VI D diesel data. In long haul and WHVC-like driving respectively, the total CO2e emissions from the LNG HPDI are more than 15% lower than for diesel but the CO2e emissions from CH4 plus N2O are higher than for diesel. In the Figure the GWPs for 100-year horizon are used (28 for CH4 and 265 for N2O); using the 20-year GWP of CH4 of 84 would heavily increase the share of CH4 in the total CO2e emissions.

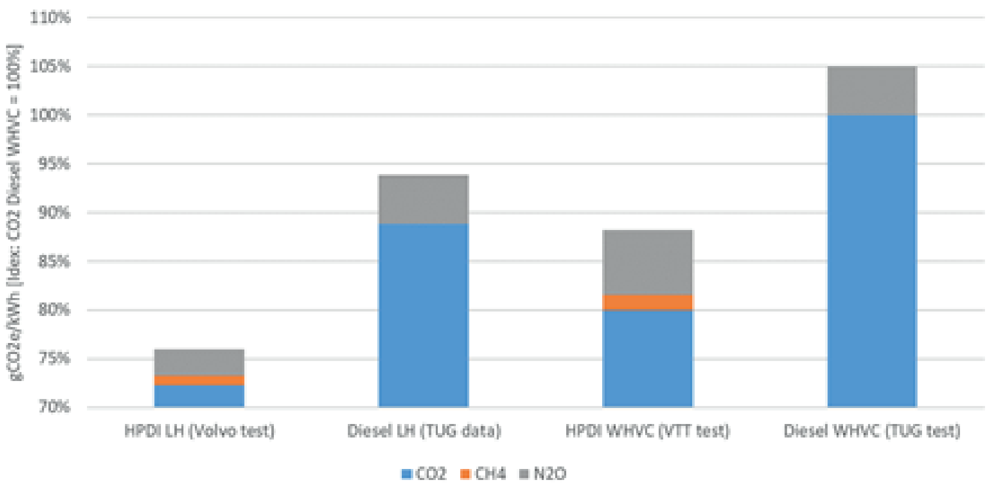


Figure 8-9: Comparison of test results for GHG exhaust emissions from LNG HPDI engine and vehicle tests with typical diesel values in a Long Haul (LH) cycle and in WHVC/WHTC tests

These emission levels of the different technologies need to be considered in the emission limits if the same limits shall be set for all technologies. Since CH_4 and N_2O have high GWP potential, both may be added to the CO_2 regulation. This option, however, would need amendments in the corresponding CO_2 regulations which is not in the scope of this study, thus this option is not followed here.

The recommended limits were elaborated for HDV similarly to the other exhaust gas components with the additional principles:

- In order not to dilute the CO_2 fleet standards of trucks, we propose that a limit should not allow for the sum of CH_4 and N_2O more than 5 to 6% contribution to the CO_2 tailpipe emissions (as CO_2e with 100 yrs. GWPs) for an average HDV trip with 7.1 x WHTC length. With such limits the average real world CO_2e contribution of CH_4 and N_2O should be less than 3%[36].
- For this exercise, we assumed as typical future real-world emission level 650 g CO_2/kWh as benchmark for “<6% contribution” target.
- In cold start conditions a higher contribution was allowed to consider the physical effects from different EATS temperature levels, in hot conditions consequently lower values were set.
- For the combined technology scenarios shown in chapter 8.5, we combined the higher limit from the different engine concepts to enable also HPDI to meet the limits.

[36] When we take ca 650g CO_2/kWh as a CO_2 level of a good EURO 7 HDV as basis, the CO_2-equivalent emission levels of the CH_4 and N_2O limits shown below can be set in relation to this direct CO2 emission level. With a 100-year GWP of 28 for CH_2 and of 265 for N_2O, the “Budget” limits for HD2 and HD3 would add ca. 5.8% to the CO_2 level and the 90th percentile hot limits would add 2.7% to the direct CO_2 emissions. Weighting the cold (budget) limits with 14% as in the current WHTC cold/hot weighting to get average HDV driving conditions, the HD2 and HD3 limits would allow 3.3% additional CO2-equivalent emissions from CH_4 and N_2O, for HL 2 and HC 2 the numbers are 5.0% and 3.8% respectively. The average real-world emissions of CH_4 and N_2O will clearly be below the limits for RDE driving, since limits also have to be met in worst-case test conditions.

Also, with this combination, the "<6% contribution" limit is met, i.e., real-world impact should be below 3%.

- The resulting limits are still very challenging. Thus, extensions are recommended:
  - The limits for CH_4 and N_2O may be combined into one limit, which could be expressed as CO_2e or also as CH_4e or N_2Oe. the sum of equivalents should be weighted according to the GWPs of CH_4 (28) and N_2O (265).
  - Since both gases do not have significant local impacts, the limits should be applicable to the entire average test result (g/test compiled from cold and hot phase limits). Meeting the limits in each MAW or in 90% of the MAWs is not needed to stay below the 6% limit goal for the worst-case. This allows more flexibility for technology design compared to a limitation for each MAW. If the MAW approach should be used for N_2O and CH_4, an increase of the limits should be considered.

Durability Requirements

In EURO VI the emission limits have to be met for N2, N3<16t, M3 until 300 000 km; for N3 > 16t until 700 000 km.

For EURO 7 an increased durability requirement is foreseen.

We have not identified any test data allowing a reliable assessment of the deterioration rates to be expected between current 0.7 and 1.2 million km. A rough assessment of expected deterioration rates is based on extrapolating deteriorations measured on EURO VI trucks between ca. 0.2 and 0.6 million km (see chapter 5) and of a demonstrator engine from the CARB Low-NOx program run at the SWRI, which uses the same technologies as the HD2 diesel in this report. The system was aged for 1 000 hours using a thermal and chemical aging process, representing 700 063 km of equivalent field operation (Sharp, 2021). Test data at 1/3 and 2/3 of the aging process are available; desulphurisation was performed regularly, the 1 000-hour test data was measured after ash removal from the filter. We extrapolated the trends to 1.2 million km and built the ratio from the extrapolated 1.2 million km to 0.7 million km. The test data and extrapolated values are shown for NOx and PM in Figure 8-10.

In (Sharp, 2021) high uncertainties on the further deterioration trends beyond the 1 000 hours are mentioned and further testing and development is suggested to produce more reliable data before extending the useful life of HDVs.

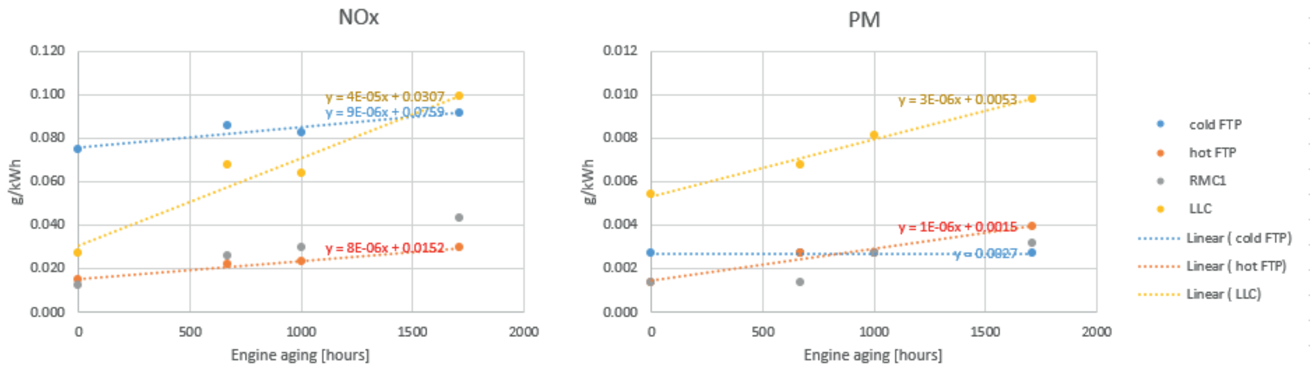


Figure 8-10: Test data on a low-NOx HDE demonstrator in different test cycles between de-greened (0 hours) and 1000 hour chemical and thermal aging and data extrapolated to 1714 hours (ca. 1.2 million km)

The resulting ratios from 1.2 million km to 0.7 million km are summarised in Table 8-5. Deterioration of the low temperature conversion efficiency of catalysts leads to highest deterioration rates in the LLC for several exhaust gas components. The LLC operates on average at ca. 7% of the rated engine power.

Table 8-5: Emission ratios between extrapolated emissions at 1.2 million km and 0.7 million km based on the test data of a low-NOx HDE demonstrator described in (Sharp, 2021); bold numbers indicate the test with the highest absolute emissions at 1.2 million km.

1.2 / 0.7 million km	NOx	CO	NMHC	CH_4 [a]	N_2O	PM
Cold FTP	111%	145%	**123%**	<100%	<100%	100%
Hot FTP	129%	173%	116%	0 at 0km	***<100%***	145%
RMC1	146%	128%	149%	0 at 0km	<100%	116%
LLC	**156%**	**165%**	70%	**110%**	<100%	**121%**

[a]: Emissions below analyser capabilities (3 mg/kWh in cold FTP, 7mg/kWh in LLC)

High uncertainties in aging effects are also reported in (Recker, 2019), which is attributed mainly to variations in the fuel and lube oil properties, such as phosphorus, calcium, sodium and sulphur content.

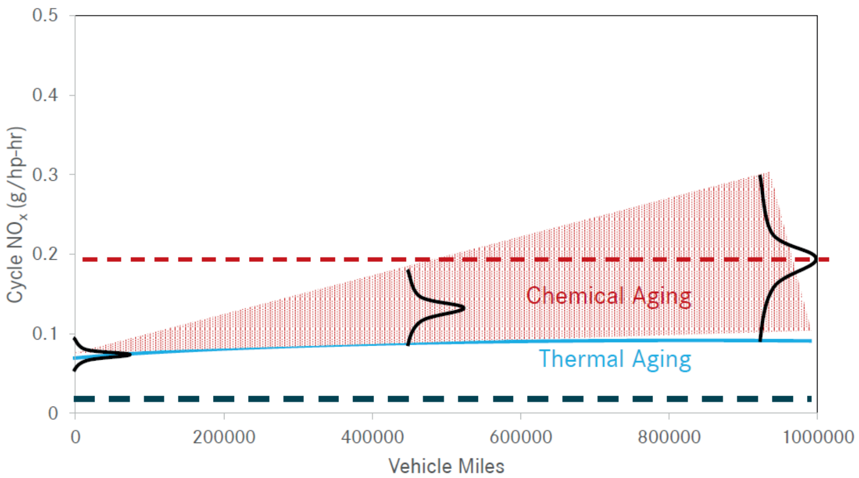


Figure 8-11: Influence of chemical and thermal aging on a HD engine (Recker, 2019)

For the set of deterioration rates possibly to be applied for EURO 7 extended useful life, we assume that possible further improvements compared to the EURO VI and to the Low-NOx demonstrator from SWRI compensate with the assumption, that the worst-case test in EURO 7 RDE driving may show more pronounced deterioration effects (lower loads than LLC possible). For CH_4 the diesel emission test data was typically below the analyser capabilities, thus we set the deterioration rates to the ones found for NMHC.

This leads to the generic deterioration factors shown in Table 8-6.

Table 8-6: Deterioration rates assessed between 0.7 and 1.2 million km for HDVs > 16t

	NOx	PN	PM	CO	NMHC	NH_3	N_2O	CH_4
HD0	170%	130%	130%	125%	190%	168%	110%	190%
HD2	160%	125%	125%	170%	150%	150%	110%	150%
HD3*	160%	125%	125%	180%	175%	150%	110%	175%

*Higher relative increases compared to HD2 are result of the lower absolute emission levels

Due to the high uncertainty, all limit values below refer to the EURO VI definition of useful life, i.e. 0.3 and 0.7 million km respectively.

One may use these limits for the EURO 7 regulation and add after the current useful life is exceeded the factors shown in Table 8-6. In any case, we think that the OBD functionalities shall be active as long as vehicles are registered in the EU.

Emission limits achievable at 0.7 million km (0.3 million km for HDV <16t)

The resulting recommended emission limits per technology are shown in Table 8-7, Table 8-8 and Table 8-9. The different limits for the different technology do not mean that we suggest different emission limits to be implemented in EURO 7. These limits instead illustrate which levels could be achievable by each of the technologies considered. The limits in combination with the “reference power” method also cover long idle conditions. A recommendation for combined limits, which consider the different levels of the engine concepts per pollutant is shown in chapter 8.5.

Table 8-7: 100th-Percentile Limits (maximum in 1xWHTC work including cold starts) for the different technologies and engine concepts for EURO VI durability requirements

mg/kWh and #kWh	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O*	CH_4*
HD 2 (opt., cc SCR)	350	5×10^{11}	12	3500	200	65	160	100
HD 3 (HD2+pre-heat)	175	5×10^{11}	12	1500	75	65	160	85
HL 2 (LNG as HD2)	350	5×10^{11}	12	7500	150	50	225	500
HC 2 (opt. CNG SI)	350	5×10^{11}	12	6500	150	70	300	450

Table 8-8: 90th-Percentile Limits (limit for hot emissions in 1xWHTC work) for the different technologies and engine concepts for EURO VI durability requirements

mg/kWh and #/kWh	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O*	CH_4*
HD 2 (opt., cc SCR)	90	1.0×10^{11}	8	200	50	65	60	50
HD 3 (HD2+pre-heat)	90	1.0×10^{11}	8	200	50	65	60	50
HL 2 (LNG as HD2)	90	1.0×10^{11}	8	300	50	50	60	350
HC 2 (opt. CNG SI)	90	1.0×10^{11}	8	300	50	70	35	300

* Limit composition for CH_4 and N_2O results in less than 5% share of CO_2e emissions vs. tailpipe CO_2 in worst-case conditions (average will be lower). Limits applicable to cycle averages, not suggested for each MAW

Note: HCHO limit is recommended as 30 mg/kWh. Simulation of the single engine concepts and technologies did not include HCHO emission. Hence, this recommendation is based on PEMS analyser capabilities and CLOVE testing of Euro VI diesel and CNG HDVs

Table 8-9: Budget Limits (maximum at 3xWHTC work including cold starts) for the different technologies and engine concepts for EURO VI durability requirements

mg/kWh and #/kWh	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O	CH4
HD 2 (opt., cc SCR)	150	2.0×10^{11}	10	1250	75	65	140	30
HD 3 (HD2+pre-heat)	100	2.0×10^{11}	10	600	50	65	140	30
HL 2 (LNG as HD2)	150	2.0×10^{11}	10	2700	75	50	200	500
HC 2 (opt. CNG SI)	150	2.0×10^{11}	10	2300	75	70	260	350

8.5 Recommended technology scenarios

The limits achievable by the single engine concepts and technologies have been compiled as a set of fuel-neutral limits. Consequently only 2 technologies remain:

- **H2**: HDV with optimised engines and close-coupled aftertreatment systems combined with underfloor systems.
- **H3**: As H2 but with preheating of the close-coupled aftertreatment system before engine starts.

To consider the high uncertainties related to the achievable future PN filtration efficiencies (e.g., ca. >95% needed for gas engines) and also possible impacts of the current uncertainties included in the (rare) test data on PN_{10} emissions from HDVs, we suggest evaluating the PN limits recommended here with further tests on HDV demonstrators using best available DPF and combustion technology as well as optimised crankcase ventilation systems.

Since HDVs have approximately the same PN level per vehicle km as LDVs (typically ca 1kWh/km engine work for heavy HDVs), somewhat higher PN limits for HDVs would not influence the overall traffic related PN emissions significantly.

As indicated in chapter 8.1, technologies needed for the H3 limits still have a considerable way to go before they are ready for series production. The risk that such limits cannot be met in serial production for all new models in 5 to 6 years from now seems quite high.

Table 8-10: Limits for the two EURO 7 technologies for EURO VI durability requirements (0.7/0.3 million kilometres) in mg/kWh (#/kWh for PN)

100th Percentile Limits	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O*	CH_4*
H2 (EURO 7 without pre-heating)	350	5.0×10^{11}	12	7500	200	70	300	500
H3 (EURO 7 with pre-heating)	175	5.0×10^{11}	12	3000	75	70	300	500
90th Percentile Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG**	**NH_3**	**N_2O***	**CH_4***
H2 (EURO 7 without pre-heating)	90	1.0×10^{11}	8	300	50	70	60	350
H3 (EURO 7 with pre-heating)	90	1.0×10^{11}	8	300	50	70	60	350
Budget Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG**	**NH_3**	**N_2O**	**CH_4**
H2 (EURO 7 without pre-heating)	150	2.0×10^{11}	10	2700	75	70	260	500
H3 (EURO 7 with pre-heating)	100	2.0×10^{11}	10	1200	50	70	260	500

* Limit composition for CH_4 and N_2O results in less than 5% share of CO_2e emissions vs. tailpipe CO_2 in worst-case conditions (average will be lower). Limits applicable to cycle averages, not suggested for each MAW

For these technologies emission factors have also been elaborated for hot driving conditions in urban, road, and motorway situations as well as temperature dependent cold start extra emissions in [g/start]. This data will be reported separately. Emission levels of different technologies compared to the limit values are also shown in “CLOVE: Task 1 Report Annexes (D.1.2); Techno-economic feasibility of new pollutant emission limits for motor vehicles; version released April 2021”.

8.6 Cost of Euro 7 technology packages

Review of supporting information

As for LDVs, this section examines the hardware costs associated with the best available technologies examined in the section above. These costs are expressed as a whole vehicle incremental cost from the baseline of Euro VI. The total hardware costs (i.e., costs of technology installed in new vehicles) for Euro VI vehicles, calculated as part of the Euro 6/VI evaluation study provided the main baseline against which the costs of EURO 7 technology packages were assessed. The total hardware costs for Euro VI vehicles, are estimated to be €1 533-€3 623 per vehicle[37]. The incremental costs expected as a result of EURO 7 were calculated from the unit hardware costs of individual components under Euro VI. Key sources which underpin the incremental cost calculations for the EURO 7 technology packages examined included cost estimates provided by ICCT, AECC/FEV,

[37] Euro 6/VI Evaluation report

alongside confidential inputs from stakeholders. The findings regarding technology costs for HDV diesel applications for post-Euro VI are summarised in the tables below.

Table 8-11: Summary of technology costs for diesel application available in the literature and from the 2nd targeted stakeholder consultation

Technology	Unit Cost [€ per system]	Euro VI D equivalent or above	Source
e-cat 48V mild hybrid	€840 – 2 100	EURO 7 (increment from Euro VI)	Diesel ICCT, 2021 presentation to AGVES; ICCT White Paper[38]
EGR **[EGR cooler]**	€439 [cooler: €108]	Euro VI (Assumed to include valve and cooler)	ICCT White Paper
SCR	€318 – 830	EURO 7 (increment from Euro VI)	ICCT White Paper; Diesel ICCT, 2021 presentation to AGVES; FEV[39]; Other[40]
SCRF	€915 – 1 055	EURO 7 (increment from Euro VI)	ICCT White paper
ASC	€93 – 221	EURO 7 (increment from Euro VI)	FEV
DPF	€427 – 738	EURO 7 (increment from Euro VI)	ICCT White Paper; FEV; Other
DOC	€260 – 726	EURO 7 (increment from Euro VI)	ICCT White Paper; FEV

NB: Costs are shown in 2020 EUR, adjusting for inflation. Upper and lower values are presented where a range of costs were found within the literature.

As well as providing their views regarding potential emission control systems to be compliant with possible future EURO 7 limits, stakeholders were also asked to estimate the cost of these emission control systems relative to the baseline of Euro VI D. In total, four stakeholders provided cost estimations for their emission control systems. These are shown in Table 8-12.

Table 8-12: Stakeholder consultation and literature incremental costs of post-Euro VI technology packages

Technology package presented	Cost increment as % increase or additional € from Euro 6VI	Source

[38] ICCT White Paper: Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles

[39] FEV (2021). EATS Cost Analysis prepared for AECC.

[40] Confidential inputs

Wastegate turbo, non-EGR, Intake throttle, Exhaust throttle, Twin SCR, Twin urea doser, DOC, DPF, AMOX	30 - 40%	Targeted stakeholder consultation
No EGR, SCR + DOC + DPF +SCR + ASC+ Twin Urea Injection	25% - 59%	Targeted stakeholder consultation
ccDOC + ccSCR/ASC +DOC+DPF+SCR/ASC+ Twin Urea Injection (Volume of SCR increased with 16l compared to Euro VI base of 34l)	14 - 33%	Targeted stakeholder consultation
EGR, 48V Electrification SCR + DOC + DPF +SCR + ASC+ Twin Urea Injection	€ 2 500	Targeted stakeholder consultation
ccDOC+SCR/ASC +DOC +DPF +SCR/ASC	€ 1 658	ICCT presentation to AGVES41, based on CARB
ccPNA + DOC + uf SCRF+ SCR/ASC (+ CDA and EGR cooler bypass)	€ 3 032	ICCT presentation to AGVES, based on CARB
EHC (48V)+ ccDOC + SCR/ASC + (uf)DOC+DPF +SCR/ASC + Twin Urea Injection	€ 3 661 (€ 5 243 with 48V)	ICCT presentation to AGVES, based on CARB

As in the case of LDVs, follow up interviews with stakeholders were also conducted to obtain additional information which provide direct inputs to the final costings for the HDV technology packages outlined in the following section. Overall, when calibrating the final costs, one of the most important tasks in the estimation of the costs was the assumptions concerning catalyst sizing and components of the different technology packages

Calculated incremental costs

The hardware cost associated with the EURO 7 technology packages is calculated as incremental cost to the latest Euro VI technologies. This cost originates either in the adaptation/optimisation of existing technologies (e.g., increased volume of catalysts) or in the introduction of additional emission control technologies (e.g., NH_3 clean up catalyst in petrol vehicles, electrically heated catalyst etc.).

The first step in the cost estimate is the calculation of the cost of individual components/technologies. The second step is the determination of the cost of the technology packages.

The first step of the procedure is the estimation of the individual component/technologies cost. The selection of the exact components is based on the previous analysis on technology packages. Table 8-13 presents the incremental cost of individual technologies and components foreseen in EURO 7 lorries and buses (the same hold also for vans, assuming larger engine capacities). With reference to particular technologies, the following are clarified:

- Where needed, a typical engine capacity of heavy lorries/buses is used.
- In the case of mild hybridisation/electrification with a 48V system, this is integrated in order to support the pre-heating functionality of the EHC. The complete cost of

41 ICCT (2021). Euro VII emissions control cost estimates. Presented to AGVES 2021.

the system is considered here, since it is not enforced by the CO_2 policy, but it is used for pollutant emission control. In the case of full hybridisation (HEV), an additional optimisation cost is considered (that is related to the necessary power electronics and the controller of the EHC), assuming that the base cost has been already encountered by the CO_2 emissions reduction technologies integrated on the vehicle.

- Some additional components (such as by-pass valves, HP EGR circuit etc.) are considered for thermal management through EGR when the SCR is still cold.
- A particle filter is introduced for CNG vehicles.
- The secondary air system is applied in the cases of preheating (either with an EHC or a burner) and when a NH_3 CUC is used in SI engines.
- Multi-gas sensors are considered for OBM.

Table 8-13: Incremental costs of individual technologies/components for EURO 7 lorries and buses (for a typical heavy-duty engine with 12.8 l displacement and 330 kW power)

Technology/ Component	Variation	Engine capacity [l]	Change EUVI → EURO 7	Unit cost [€ or €/l]	Total cost [€]
Diesel					
Hybrid system	Support of e-cat (wiring, power electronics, controllers)	All	0 → 1	800	800
	48 battery (~5-7kWh) for preheating functionality of e-cat	All	0 → 1	1500	1500
	HEV optimization	All	0 → 1	500	500
EGR when SCR is cold (thermal management)	Further improvement	All	0 → 1	100	100
DOC	Increased volume	12.8	11.4l → 14.0l	43.9	114.2
	Improved durability	12.8	11.4l → 14.0l	43.9	61.5
	Replacement (in 30% of the fleet)	12.8	0 → 14.0l	43.9	184.5
SCR	Increased volume	12.8	21.3l → 37.5l	20.4	330.5
	Improved durability	12.8	21.3l → 37.5l	20.4	76.5
	Replacement (in 30% of the fleet)	12.8	0 → 37.5l	20.4	229.5

Technology/ Component	Variation	Engine capacity [l]	Change EUVI → EURO 7	Unit cost [€ or €/l]	Total cost [€]
ASC	Increased volume	12.8	7.1l → 12.5l	16.0	86.4
	Improved durability	12.8	7.1l → 12.5l	16.0	20.0
Optimised DPF	Coated filter	12.8	0 → 1	60	60
Close-coupled components packaging	Introduction in EURO 7	All	0 → 1	500	500
Twin urea dosing	2nd injector	All	1 → 2	100	100
e-cat 15kW (EHC)	without preheating	All	0 → 1	250	250
	with preheating (×4)	All	0 → 4	250	1000
Fuel burner 60kW	without preheating – no new HW (HC doser)	All	0 → 0	1500	0
	with preheating	All	0 → 1	1500	1500
Secondary air injection	For cases with preheating	All	0 → 1	100	100
Multi-gas sensor	Introduction in EURO 7	All	0 → 1	300	300
OTA data transmission	Introduction in EURO 7	All	0 → 1	60	60
Natural Gas					
Hybrid system	Support of e-cat (wiring, power electronics, controllers)	All	0 → 1	800	800
	48 battery (~5-7kWh) for preheating functionality of e-cat	All	0 → 1	1500	1500
	HEV optimization	All	0 → 1	500	5000
EGR when SCR is cold (thermal management)	Further improvement	All	0 → 1	100	100
DOC	Increased volume	12.8	11.4l → 14.0l	43.9	114.2

Technology/ Component	Variation	Engine capacity [l]	Change EUVI → EURO 7	Unit cost [€ or €/l]	Total cost [€]
SCR	Improved durability	12.8	11.4l → 14.0l	43.9	61.5
SCR	Replacement (in 30% of the fleet)	12.8	0 → 14.0l	43.9	184.5
SCR	Increased volume	12.8	21.3l → 37.5l	20.4	330.5
SCR	Improved durability	12.8	21.3l → 37.5l	20.4	76.5
SCR	Replacement (in 30% of the fleet)	12.8	0 → 37.5l	20.4	229.5
ASC	Increased volume	12.8	7.1l → 12.5l	16.0	86.4
ASC	Improved durability	12.8	7.1l → 12.5l	16.0	20.0
Optimised particulate filter	Coated filter	12.8	0 → 1	60	60
TWC for CNG λ=1	Increased volume	12.8	10.0l → 15.0l	80	400
TWC for CNG λ=1	Improved durability	12.8	10.0l → 15.0l	80	120
TWC for CNG λ=1	Replacement (in 30% of the fleet)	12,8	0 → 15.0l	80	360
GPF	Introduction in EURO 7	All	0l → 12.8l	57.2	733
Close-coupled components packaging	Introduction in EURO 7	All	0 → 1	500	500
Twin urea dosing	2nd injector	All	1 → 2	100	100
e-cat 15kW (EHC)	without preheating	All	0 → 1	250	250
e-cat 15kW (EHC)	with preheating (×4)	All	0 → 4	250	1000
Fuel burner 60kW	without preheating – no new HW (HC doser)	All	0 → 0	1500	0
Fuel burner 60kW	with preheating	All	0 → 1	1500	1500
Secondary air injection	For cases with preheating	All	0 → 1	100	100
Multi-gas sensor	Introduction in EURO 7	All	0 → 1	300	300

Technology/ Component	Variation	Engine capacity [l]	Change EUVI → EURO 7	Unit cost [€ or €/l]	Total cost [€]
OTA data transmission	Introduction in EURO 7	All	0 → 1	60	60

In the second step, the total cost of the complete EURO 7 technology packages is calculated by synthesising the cost of individual components, considering the share of each segment. The calculated costs are presented in Table 8-14.

Table 8-14: Cost of each EURO 7 technology package considered for lorries/buses

Diesel	
Short name	Incremental cost compared to Euro VI [€]
HD0 – Average 2020	0
HD1 – Best 2020	0
HD2 – ccEATS opt	1863
HD2 – ccEATS opt e-cat	2913
HD3 – ccEATS opt burner preheating	3463
HD3 – ccEATS opt e-cat preheating	5263
HD4 – HEV ccEATS opt burner preheating	3963
HD4 – HEV ccEATS opt e-cat preheating	5763
Natural Gas	
Short name	Incremental cost compared to Euro VI [€]
HL2 – LNG HPDI	1863
HL2 – LNG HPDI e-cat	2913
HC2 – CNG	2113
HC2 – CNG e-cat	3163

9 Findings on evaporative emissions

The fuel vapours released from petrol vehicles are mostly volatile organic compounds (VOCs), not associated with the combustion process of the ICE. VOCs contribute to the formation of ground-level ozone and secondary organic aerosols. The dominant sources of fuel evaporation from vehicles are the fuel tank ventilation system and the permeation through the walls of the fuel tank and hoses. Small leaks of liquid or fuel vapour, caused by for example corroded fuel lines, filler neck, cracked hoses, etc., can be an additional source of emissions.

In general, evaporative emissions occur (1) during vehicle operation (running losses), (2) immediately after the vehicle's engine is switched off after operation (hot soak), (3) during vehicle parking with the engine switched off (diurnal emissions), and (4) during refuelling. In addition to the fuel emissions, other non-fuel hydrocarbon emissions from plastics, rubber and other polymers found in tyres, carpets, seats, paints, adhesives, etc. may also add up to the total evaporative emissions.

9.1 Current Emission Standards

A revised legislative test procedure, within the UNECE level (WLTP), has been recently introduced to better control evaporative emissions for Euro 6d-temp and Euro 6d. The testing requirements regarding evaporative emissions are also outlined in Annex VI of Regulation (EU) 2017/1151, as amended by Regulation (EU) 2018/1832. They include the main evaporative emissions test and two additional tests, one for the ageing of the carbon canister and one for assessing the permeability of the fuel storage system. The new test provisions have become mandatory for LDVs since September 2019 and apply to both petrol and bi-fuel vehicles with PI engines (including HEVs).

9.1.1 In operation and parked

Until now, evaporative VOC emissions have only been regulated for LDVs with PI engines that run on petrol or have bi-fuel capabilities. Type 4 testing includes evaporative emissions test provisions that conform to the requirements of the UN Global Technical Regulation No.15 of the UNECE (European Commission, 2017). However, these test procedures under the WLTP provisions only determine evaporative emissions when the vehicle is parked. This procedure determines VOC emissions during a one-hour hot soak test at constant temperature, followed by a 48-hour diurnal test over a specified temperature profile (20–35°C). Evaporative VOC emissions occurring during vehicle operation are currently not regulated in the EU.

9.2 Evidence on evaporative emissions contribution

As demonstrated in Figure 9-1, according to the data submitted via the EU emission inventory reports under the LRTAP, evaporative VOC emissions from petrol vehicles account for a substantial and increasing share of total vehicle emissions, as tailpipe VOC emissions continue to decrease. If considering VOC emissions from petrol vehicles only, the share of evaporative emissions is even higher, being the same order of magnitude as exhaust emissions.

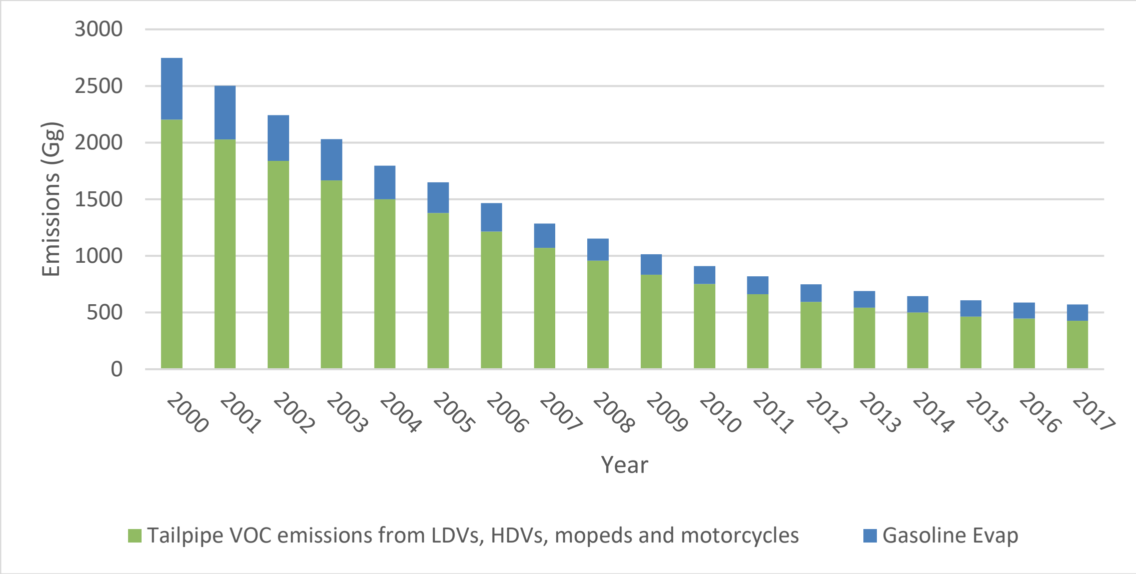


Figure 9-1: Evaporative emissions of NMVOCs per year for the EU28 as a share of total transport NMVOC emissions (European Enviroment Agency, 2020)

9.2.1 Diurnal emissions

Diurnal emissions result from the evaporation of fuel due to temperature fluctuation during the day. The recently updated EU procedure and regulatory limits cover a good part of typical EU driving and parking conditions. However, evaporative emissions under extreme conditions may not be sufficiently controlled, such as:

a. During very short trips or congested traffic situations. In these cases, typically in urban environments, canister purging might not be sufficient due to short trip duration or due to low or no purging during idling. As a result, the canister working capacity going into a parking event is reduced compared to a fully purged canister.

b. During very high ambient temperatures (above 35°C), which are becoming more frequent in Europe. Especially when combined with increased parking durations that may occur during the summer period, this can lead to significant increases in the amount of fuel vapour generated in the fuel tank that may exceed the capabilities of typical canister sizes.

9.2.2 Running losses

Ideally, they can be measured in a Sealed Housing for Evaporative Determination (SHED) equipped with a chassis dynamometer. However – to the best of our knowledge – there is no such testing facility in Europe and hence there is little relevant experience or test data. An alternative test method includes the so-called “point-source method”, where the vehicle is driven on a chassis dynamometer under specific conditions and potential emission sources are checked with a vapour collection system. Various US studies suggest that running losses can be significant due to high temperature build-up in the fuel tank during normal vehicle operation. A recent JRC study (Grigoratos et al. 2019) has shown that the difference between tank and ambient temperature during individual trips can vary between 1 and 10 °C depending on the testing conditions and may increase even further with driving time. Such temperature build-ups in the fuel tank, combined with reduced purge rates, may result in high vapour load rates that a typical canister will be unable to handle.

9.2.3 Refuelling emissions

Refuelling emissions are fuel vapours that escape from the filler neck of the tank due to their displacement by liquid fuel. These emissions are currently controlled in the EU by means of the so-called Stage II petrol vapour recovery system (Directive 2009/126/EC), in which the fuel nozzle is designed to draw the air/petrol vapour mixture displaced by the liquid fuel entering the tank and to route it to the underground petrol storage tank of the service station. Currently, most (large) service stations (over 500 m^3 annual throughput) are compliant with Stage II requirements. In 2016, at least 65-75% of total service stations were equipped with Stage II recovery systems, covering 60-70% of total petrol dispensed (European Commission , 2017). These figures have most likely increased in recent years; however, no data exist at the EU level.

The service stations equipped with Stage II are required to have a petrol vapour capture efficiency that is equal to or greater than 85%. In practice, this figure may be lower depending on facility maintenance. In the US much lower real-world efficiencies were reported (typically in the range of 50-60%) which led to the introduction of Onboard Refuelling Vapour Recovery system (ORVR). This report only addresses how vehicles may be enhanced to reduce their emissions, therefore issues such as inefficiencies regarding service station underground storage tanks or fuel pumps fitted as per Stage II requirements are not addressed.

In other countries such as the USA, China and Brazil, the installation of ORVR is mandatory to control refuelling emissions. This technology is further discussed in Section 9.3 of this report.

9.2.4 Vapour leakages

Leaks of liquid or fuel vapour are caused by corroded fuel lines, filler neck, cracked hoses, etc. Leaks are currently not detected in the EU. US data (EPA, 2014, 2010) show that ~3% of vehicles have cracks greater than 1 mm of diameter and that this number is higher in areas without Inspection & Maintenance. Emissions can be significant – in the order of several grams per day – depending on leak size. The same data suggest that up to 30% of cars older than 10 years emit more than the current limit of 0.02 inch (~0.5 mm). It is noted that the existing OBD systems in the US are able to detect leaks on the vapour side only, whereas leaks on the liquid side are not detected.

The OBD requirement regarding evaporative emissions in the EU only consists of checking the integrity of the purge valve's electrical circuit. But this provision does not indicate a failure to the driver, in case of a leakage in the fuel system or a blocked line.

9.2.5 Future ethanol blends

As also discussed under Section 3.1.1 for tailpipe emissions of formaldehyde, fuels with higher ethanol contents are gaining traction within the market. Ethanol has been found to increase the evaporative VOC emissions from vehicles due to increased permeation of fuel tank lining, its negative effect on the effectiveness of the carbon canister, increased vapour pressure and co-mingling of fuel (Martini, et al., 2012). Therefore, as fuel ethanol content increases in vehicles, it may be expected that the contribution of petrol vehicles to evaporative VOC emissions will increase.

This is particularly true if the ethanol content in pump petrol increases to 10% (by volume), as is permitted by Directive 2009/30/EC, and especially when ethanol and non-ethanol containing fuels are mixed (co-mingling effect). On higher ethanol blends (E20/E25), a recent study (Netherlands Standardization Institute, 2020) conducted on behalf of the CEN (European Standardization Committee), under a specific EC Horizon2020 call, reports higher evaporative emissions with increasing ethanol content, but still below the emission limit.

9.3 Technologies for reducing emissions

To some extent, similar technology solutions can be employed to reduce evaporative emissions during all stages of vehicle use, whether it is refuelling, parked or in operation. These technologies are outlined in the table below and described in detail in the following paragraphs.

Table 9-1: Vehicle Technologies to reduce evaporative emissions

Top	Carbon canister	ORVR	Low permeability materials	Sealed fuel tanks	OBD leak detection
Diurnal and hot soak	X	X	-	X	-
Running losses	X	X	-	X	-
Refuelling	-	X	-	-	-
Leaks	-	-	-	-	X
Permeation	-	-	X	-	-

The **activated carbon canister** is the main component of the evaporative emission control system. The canisters employed on petrol vehicles consist of a plastic housing containing high surface area carbon adsorbent material. Canister loading occurs during diurnal events and refuelling. Canisters come in many shapes and sizes and are sized to be proportional to the possible volume of vapour generated in the fuel tank.

Advanced canisters employ multiple chambers and specially designed carbon adsorbents to achieve very low or zero evaporative emissions depending on the level of evaporative emission that must be achieved. As fuel vapours are displaced from the tank during heating or refuelling (for ORVR equipped vehicles), they enter the first chamber of the canister and pass through to the second chamber. Hydrocarbon molecules are attracted to the non-polar surface of the activated carbon and stored within the pores by physical adsorption. During engine operation, fresh air is purged through the canister to regenerate the carbon. The purged vapours are burnt in the combustion chamber along with the fuel mixture.

On-board refuelling vapor recovery (ORVR) systems are designed to capture fuel vapour that are displaced from the fuel tank during refuelling. The displaced vapour is directed into the activated carbon canister where it is adsorbed. In addition to the carbon canister, there are several other valves and seals to prevent escape of vapour through the fuel filler pipe and preventing liquid fuel from exiting the fuel tank.

Vehicles equipped with ORVR have the following design changes:

- The diameter of the filler neck is reduced to create a liquid seal during refuelling.
- A check valve installed at the bottom of the fill pipe to prevent fuel spit-back.
- A low-pressure drop valve is added to the fuel tank.
- The vent line leading to the carbon canister is replaced with a larger diameter hose; this results in less resistance and hence an easier flow of the displaced vapours to

the canister. This change is offset by reducing the diameter of the hose to the top of the fill pipe.

- The canister capacity is increased to accommodate the increased vapour load and load rate from refuelling. The canister must have a low pressure drop to prevent premature shutoff during refuelling.
- The vehicle must be recalibrated to increase purge rates to accommodate the higher vapour capacity of the canister.

Low-permeability materials can be used to control permeation emissions. Although metal tanks offer the highest barrier to permeation, they add weight and limit the shape necessary to meet stringent packaging requirements. Advanced tanks consist of coextruded, multilayer construction with a barrier layer of ethylene vinyl alcohol and fluoropolymers to reduce permeation. Furthermore, polymers can be treated via sulfonation or fluorination to further reduce permeability. Similar approaches of material selection can be applied to fuel hoses, seals, fuel caps and gaskets used within the fuel system. The use of coextruded, low permeation polymers such as nylon, fluoropolymers, and fluoroelastomers can be employed in fuel lines to significantly reduce permeation emissions. Special challenges in permeation emissions and materials compatibility have resulted since the introduction of ethanol blends in petrol fuel. The newest vehicles and, in particular, Flexible Fuel Vehicles are equipped with the lowest permeation materials in the fuel tanks, hoses, seals and gaskets.

Sealed tanks are mostly employed for hybrid vehicles as they have limited opportunity of purging when operated in electric mode. A vapour control valve is used to close the path from the fuel tank to the canister when the engine is not running, thus suppressing vapour emissions. A pressure-resistant fuel tank (usually metal) is needed to withstand the high pressure. As an additional measure to minimise vapour generation, heat insulation may also be applied to minimise heat transfer from engine, exhaust, road surface, etc. During refuelling, the vapour control valve opens to release pressure in the tank and the fuel vapour is introduced to the canister.

Two types of **OBD leak detection** are currently available. The active leak detection is based on a pump system which pressurises or depressurises the fuel tank. The pressure in the system is compared to a reference value and a leak is detected when the measured pressure doesn’t reach the refence pressure. The passive leak detection system compares in-tank pressure at high temperature and low temperature. Normally the difference in pressure measured should be high, but in case of leaks it becomes small.

9.4 Emission levels achievable

Evidence presented by MECA (2020) regarding the US’s experience with ORVR suggests that implementation of ORVR results in emission savings nearly 30% greater than those achieved by Stage II over a vehicle’s lifetime. The increased canister capacity of ORVR, combined with a more aggressive purging strategy, will also enable a more effective control of diurnal, hot soak, and running loss emissions under more severe conditions, such as at elevated temperatures and during short trips. Hence, much lower emission levels during the standard SHED test can be achieved without the need of any additional technology (Martini, et al., 2012).

The emission levels achievable with the implementation of different fuel vapour control technologies are summarised in Table 9-2:.

Table 9-2: Evaporation control technologies and achievable levels

Technology	Specifications	Emission levels
Euro 6		
Activated carbon canister	1.0 – 1.5 L for a 50 – 75 L fuel tank 44 – 55 g/L GWC*	< 1.0 g/day (diurnal emissions) of which 0.5 – 0.7 g (canister emissions) 0.15 – 0.2 g (permeation) 0.1 g (background)
Purging strategy	12 – 16 L/km	
Stage II control	70% efficiency assumed (55 – 85%)	20 – 30 g/refuelling, or 0.4 g/L fuel dispensed
Post Euro 6		
Activated carbon canister	1.5 – 2.2 L for a 50 – 75 L fuel tank 70 – 80 g/L GWC*	< 0.3 g/day (diurnal emissions) of which < 0.1 g (canister emissions) < 0.1 g (permeation) < 0.1 g (background)
Purging strategy	25 – 30 L/km	
ORVR	97% efficiency assumed	2 – 3 g/refuelling, or 0.04 g/L fuel dispensed

* GWC: Petrol working capacity

9.5 Recommended emission limits

The current testing procedure and emission limits will have to be revised to make sure that emissions under more severe driving (short driving events and lengthy driving events at high temperature) and climatic conditions (extended parking events at high temperature) are effectively controlled.

More specifically, a reduced emission limit is recommended for the diurnal test. Whereas the duration of the test is recommended to remain as is (48 hours), the limit is expressed in grams per day for consistency with other jurisdictions (such as USA and China). In this case, an emissions result is determined for each of the two days of the SHED test and the highest (including hot soak) is compared to the limit. A distinction is made on the basis of vehicle size, to account for non-fuel background emissions, which are generally higher for larger vehicles. Therefore, there is one limit for passenger cars and small light commercial vehicles (<2.5t TPMLM) and a higher limit for heavier light commercial vehicles (>2.5t TPMLM). To ensure sufficient purging prior to the SHED test, the soak and drive temperature is not prescribed, but can range from 25 to 38°C.

A limit for refuelling emissions is also recommended. Increased canister capacity and higher purge rates will be needed to comply with both the diurnal and the refuelling emission limits.

For running losses, no dedicated limit is deemed necessary if the suggested limits on diurnal and refuelling emissions are adopted. The increased canister capacity and higher purge volumes will ensure that running losses are kept at minimum levels.

Finally, it is also suggested to include OBD leakage detection requirements. A threshold of 0.5 mm (~0.02 inch) for the minimum leak diameter to be detected is recommended.

A summary of the recommended limits and related testing conditions are summarised in Table 9-3 and Table 9-4 respectively.

Table 9-3: Recommended evaporative emission limits

	PCs and LCVs < 2.5t TPMLM (N1 class I-II)	LCVs > 2.5t TPMLM (N1 class III)
Diurnal emissions limit	0.50 g/day (48 h test, worst of 2 days)	0.70 g/day (48 h test, worst of 2 days)
	0.30 g/day (48 h test, worst of 2 days)	0.50 g/day (48 h test, worst of 2 days)
Refuelling emissions (ORVR)	0.05 g/L	
Leak threshold	0.5 mm (~0.02 inch) diameter	

Table 9-4: Testing conditions

	Testing conditions	Comments
Preconditioning	• Soak and drive temperature between 25°C and 38°C	• Enforce more frequent purging • Exact temperature not defined to prevent tuning of purging strategy
SHED test	• 48-h diurnal test (+hot soak) remains as is • Hot soak temperature at 38°C	• Emission limit applies to worst of two days (+hot soak)
Running losses	• No test and hence no limit during certification	• Running losses effectively controlled by the technology used to achieve lower diurnal emissions
ISC and MaS	• Diurnal emissions (and indirectly also running losses) checked during ISC and MaS	
OBD leak detection	• Checked during PTI, ISC, MaS	
Background emissions	• Baking of entire vehicle or of individual components (optional)	• SHED test run with used tyres (optional)

9.6 Costs of emission control technologies

Table 9-5 summarises the costs of the technologies of Table 9-2. In addition to the hardware cost of the different components, other associated costs such as for R&D and calibration, for testing, and for certification are also included in the same table. For the estimation of these costs, inputs from stakeholders were combined with information from the literature and expert knowledge.

It is noted that calibration refers to the engineering and testing activities required to adjust the performance of the selected emission control technology to the specifications of a particular vehicle model or engine type. As such, the cost in the table is indicative only and provides a rough estimation of the total calibration costs for a new vehicle model that includes various new components, not only for evaporation control.

Table 9-5: Cost of evaporation control technologies

Component	Unit (cost per)	Cost (€)
ORVR carbon canister for 0.5g/test	New registration	10
Anti spitback/vapour seal valve	New registration	2
Purge valve	New registration	2
Tank vent hose	New registration	2
Larger ORVR carbon canister for 0.3g/test	New registration	4
Low permeability tank and hoses	New registration	20
Pump system for OBD leak check	New registration	25
R&D/calibration/engineering costs	Engine/model family	1 000 000
Certification / Admin costs	New registration	0.2

10 Findings on brake and tyre wear emissions

10.1 Overview

Brake and tyre wear are examples of non-exhaust emissions of particulate matter originating from abrasion processes. In the stakeholder consultation (CLOVE consortium, 2019), more than a third of respondents expressed the belief that non-exhaust emissions (evaporative, brake and tyre) should be included in EURO 7 to ensure that pollution from all sources is reduced to the lowest possible level, and the number of stakeholders supporting the addition of brake and tyre wear as new regulated emissions was similar to those supporting the adoption of ammonia.

The vast majority of brake and tyre wear mass is indeed a result of abrasion processes; however, it has been demonstrated that both sources can emit ultrafine particles under certain conditions. The ultrafine fraction of brake and tyre particles is a result of thermochemical processes. Other non-exhaust emissions include road surface wear, corrosion, and resuspension of pre-existing deposited material (Wakeling, et al., 2018). Some researchers consider re-suspended dust as a non-exhaust traffic-related source. However, existing dust can be suspended also due to other reasons (i.e., meteorological conditions); therefore, it is questionable whether it should count as a non-exhaust traffic-related source. Furthermore, the properties and fate of pre-existing deposited material largely depends on conditions not related to traffic (i.e., topography, meteorological conditions, type of site, etc.) and cannot be controlled. This chapter will specifically address emissions associated with brake wear and tyre wear as these are recognised as two of the most important emission sources in terms of their contribution to overall non-exhaust emissions from transport (Grigoratos & Martini, 2014; Grigoratos 2021). Tyre and brake wear emissions constitute both coarse and fine particles and are a concern for both PM and PN emissions.

A recent study by the OECD (OECD, 2020) used literature and emissions factors to propose that EVs and HEVs will likely have increased non-exhaust $PM_{2.5}$ emissions compared to ICE vehicles. Increased EV tyre wear emissions of $PM_{2.5}$ were attributed to elevated vehicle weight, and OECD estimate that the $PM_{2.5}$ increase from tyres will be high enough to overcome the reduction of EV brake-wear emissions due to regenerative braking. However, it should be noted that tyre wear production of $PM_{2.5}$ is generally much lower than PM_{10} from all vehicles, and any benefits in reducing tyre wear from regenerative braking were not accounted for by OECD. Furthermore, the effect of ADAS and car-to-car communication systems in reducing brake emissions of EVs have not been taken into account, whereas the tendency for continuously producing lighter batteries has been ignored. Finally, none of the recommended emission values were validated experimentally. Further work is required in this area to understand the effect of the fleet electrification to non-exhaust emissions.

Brake wear emissions occur as a result of both mechanical processes, due to the impact of friction on brake linings and discs during braking events, and volatilisation processes involving materials within the brake pads (Wakeling et al, 2018) but also on the disc surface as a result of extremely high local temperatures. Studies have found that emissions caused by mechanical processes tend to be larger and coarser, therefore make-up almost all mass emissions. On the other hand, emissions resulting from volatilisation processes tend to be much finer, are highly correlated to brake temperature, and make-up the vast majority of PN concentrations (Thorpe and Harrison, 2008; Pant & Harrison, 2013; Wakeling et al, 2018; Mathissen et al, 2019). Recently presented data indicate that $PM_{2.5}$ make up approximately one third of overall PM_{10} brake particle emissions (Grigoratos 2021).

Similarly, **tyre wear** emissions are also generated mechanically, due to friction between the tyre tread and the road surface, or by volatilisation (Grigoratos & Martini, 2014). Some researchers have reported that tyre wear particles are a mixture of tyre, road, and dust material; therefore, no pure tyre wear particles exist in the environment (Kreider et al, 2010). However, this assumption might only apply to particles coming from abrasion processes and not to ultrafine tyre emissions. Studies report that ultrafine concentrations are generally low (Grigoratos et al, 2018) and typically correlate with “non-typical” or “extreme” driving conditions (Mathissen et al, 2011). Further data and standardisation of the sampling and measurement methods are required to fully characterise tyre wear emissions.

10.2 Current Emission Standards

There is currently no legislation in Europe that explicitly regulates emissions as a result of tyre wear. While the European Tyre Labelling Regulation 1222/2009/EC does require the labelling of tyres regarding their impact on fuel efficiency and other measures such as wet slip, there are no requirements regarding the durability of the tyre. However, for the first time, the EC has mandated the development of a methodology for measuring tyres’ abrasion rate. The concept of abrasion rate relates to microplastic emissions and concerns the overall material released from the tyre and not only its PM_{10} emissions. Up to now, there has been no established correlation between total material release and PM/PN emissions (Grigoratos et al, 2018). This topic will be further investigated by the PMP IWG as well as the H2020 Project consortium LEON-T once the methodology for measuring tyres’ abrasion rate is developed.

Worldwide regulations affecting brake and tyre composition have been described recently (Grigoratos, 2018). However, there is currently no legislation in Europe – or any other part of the world – that explicitly regulates emissions as a result of brake or tyre wear. US prescribe standards for the grading of tyre treadwear (49 CFR § 575.104) by testing tyres driven over a prescribed route for a distance of up to approximately 10 000 km (6 400 miles) and by measuring the tread depth decrease in the course of testing. Although this procedure does not target tyre-related emissions per se, tread wear rate is a key indicator for emissions rate. Obviously, depending on tyre composition and design, wear can result to airborne or larger non-airborne particles. For example, the wear rate of tyres for passenger cars are in the order of 100 mg/km while PM_{10} emission factors is in the 10 mg/km range (EEA, 2019b). More detailed EFs have been presented recently in the framework of the ERMES Plenary session (Gustafsson 2021).

The Particle Measurement Programme Informal Working Group (PMP-IWG or PMP) has been mandated by the United Nations Working Party on Pollution and Energy (UNECE-GRPE or GRPE) to develop a methodology for sampling and measuring brake particle emissions. The initial intention of the GRPE was to provide the scientific community with a commonly accepted tool to characterise brake emissions. However, the increased interest on non-exhaust emissions led several GRPE contracting parties to urge the PMP to start considering a possible use of the method as a regulatory tool. The method is still under development and is expected to be completed by the end of 2021. The GRPE started discussing the way forward on brake emissions regulation in January 2021 following the organisation of a workshop dedicated to brake emissions (PMP, 2021).

10.3 Evidence on Euro 6/VI contribution

As shown in Figure 10-1, according to the data submitted via the EU emission inventory reports under the LRTAP, tyre and brake wear constitute a significant share of overall particulate matter emissions from the transport sector. In 2017, it appears that the emissions from tyre and brake wear are equivalent to the levels of emissions that originate from the exhaust of both HDVs and LDVs. This conclusion is also reached within the existing literature. While Figure 10-1 refers only to $PM_{2.5}$ emissions, brake and particularly tyre wear emissions also contribute significantly to the coarse fraction PM_{10}. This suggests that non-exhaust emissions may already surpass exhaust emissions, at least in countries where the vehicle fleet is relatively new (Jeong et al, 2020).

One point that requires special attention relates to future projections. According to the existing literature it is expected non-exhaust contribution to vehicle related PM_{10} emissions to overcome 90% in the next few years. However, these projections do not take into account the positive impact of future technologies – including regenerative braking – to brake emissions. Preliminary studies indicate that HEVs and EVs emit significantly lower brake PM_{10} and $PM_{2.5}$ compared to conventional vehicles (Agudelo et al. 2020). Therefore, these projections might need to be updated regularly to account for technology developments.

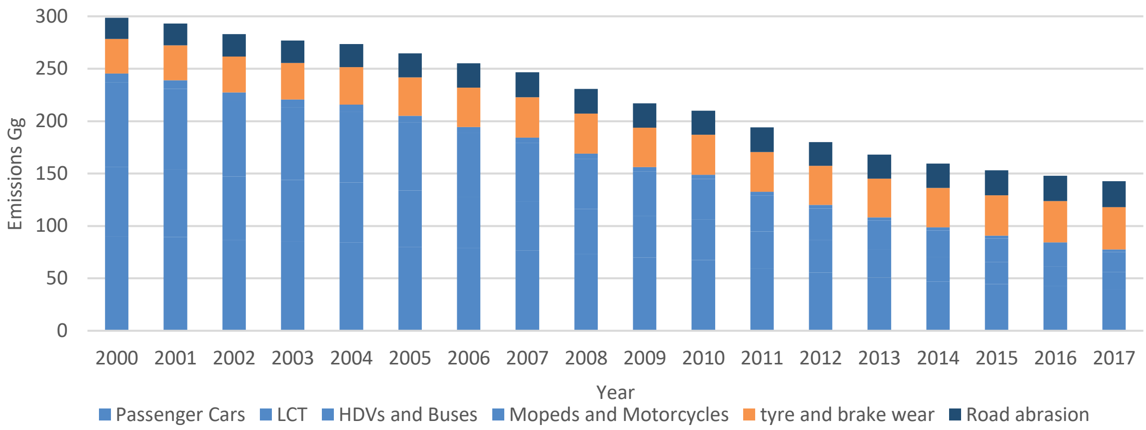


Figure 10-1: Tyre and Brake wear emissions of $PM_{2.5}$ as a Share of Total Transport Sector Emissions (EEA, 2020)

A review of the relevant literature conducted by Wakeling et al. (2018) reported that the contribution of **brake wear** to ambient PM_{10} concentrations at European 'urban roadside sites' is estimated to be between 0.8 μg m^{-3} to 5 μg m^{-3}. This is very close to brake PM_{10} values up to 4 μg m^{-3} reported previously (Grigoratos and Martini, 2015). However, there are uncertainties that exist around the measurement of the contribution of brake wear to primary particle emissions. There are several reasons for this. Primarily, brake wear emissions are measured using a chemical tracer, which is thought to be present only in the vehicle brakes. These tracers frequently include copper and iron. However, brake wear emissions are highly variable in terms of the components that they include. Therefore, it is difficult to identify one chemical tracer that is able to reliably identify all brake wear emissions. Additionally, copper has been a subject of regulation in parts of the US and as a consequence many brake pad manufacturers are phasing out this element from their products. The regulation concerns only part of the US; however, it affects also the European market due the global character of the brake industry. Another issue arises when differentiating between emissions that are the direct result of brake wear occurring at the time of measurement, and those that are due to resuspension of particles which could include previously emitted brake wear (Wakeling, et al., 2018). Even when road dust resuspension is not taken into account as a non-exhaust source, double counting might occur when applying source apportionment techniques to calculate the contribution of **brake wear** to ambient PM_{10} concentrations by means of chemical tracers.

In the case of **tyre wear**, a review of existing studies by Grigoratos and Martini (2014) states that while tyre wear is found to contribute between 5-30% of non-exhaust emissions by mass, its contribution to ambient PM_{10} concentration levels is estimated to be between <1% and 7%. However, the report also emphasises the shortcomings of measurement techniques: it is difficult to exclude emissions from road wear from measurements; that measurements are influenced by the chemical tracer used within the analysis; and that measurements are influenced by the conditions of the sample site. Tyre wear contribution to ambient $PM_{2.5}$ concentrations of 0.2–7.0% by mass was recently reported by Panko et al. (2018). The European Tyre & Rubber Manufacturers Association has reported – through their TIP Project – contributions to the lower range of the above intervals [Panko et al., 2013],

Overall, it is generally concluded that while non-exhaust PM emissions are of a similar scale to exhaust PM emissions, as demonstrated in Figure 10-1, as exhaust emissions from road transport are subject to increasingly stringent standards, the relative contribution (%) of non-exhaust emissions to overall PM will increase. This indicates that, in the future, this is the area where further reduction of the on-road transport sector's contribution to particle emissions will need to be focused.

For each of brake and tyre wear sources, the Atmospheric Emissions Inventory Guidebook (EEA, 2019b) indicates that passenger cars are currently found to emit PM_{10} in the order of 7.5-10 mg/km, for average travelling speeds of around 65 kph. Slightly higher emission factors for both sources were reported in the 2021 ERMES Plenary Session. A recent review carried out by the Air Quality Expert Group in the UK in 2019 found that emission factors within the literature are not directly comparable due to the range of methods by which they were obtained. Furthermore, the methods employed have meant that these factors do not accurately distinguish between different vehicle classes, or brakes and tyres with different characteristics (Air Quality Expert Group (AQEG), 2019).

For brake PM_{10} EFs, values to the upper range of the aforementioned interval seem to be confirmed by recently published data from a large scale H2020 Project on brake emissions (LOWBRASYS). More specifically, PM_{10} EFs in their study range between 1.8 - 4.4 mg km^{-1} per brake corner. These values correspond to approximately 5.4 – 13.2 mg km^{-1} per vehicle and were derived on a brake dyno with the application of a relatively aggressive braking cycle (Short-LACT). PMP members have reported PM_{10} EFs in the range of 7.0 mg km^{-1} $vehicle^{-1}$ to 15 mg km^{-1} $vehicle^{-1}$ for the European-type LS pads and 3.5 mg km^{-1} $vehicle^{-1}$ to 5 mg km^{-1} $vehicle^{-1}$ for the US-type non-asbestos organic (NAO) pads (Hagino et al. 2019; Robere et al. 2019; Mamakos et al. 2021; Hesse et al. 2021). Although direct comparison is not straightforward, due to the different vehicle classes involves in each study, overall, there seems to be a consensus that brake PM_{10} and $PM_{2.5}$ EFs depend on the type of the friction material with low steel (LS) pads emitting 3-4 times higher than NAO pads (Agudelo et al. 2020; Grigoratos 2021). No data regarding updated tyre PM emissions have been published recently at the time of writing.

10.4 Best available Technologies for reducing emissions

10.4.1 Brake Wear Control Technologies

Within the literature there are several technologies that are suggested to reduce brake wear particulate matter. These technologies can be categorised into those that act to reduce the formulation of particulate emission and those that contain particles after they are formed.

Currently used brake system configurations can be categorised into those that employ disc brakes and those that employ drum brakes (Air Quality Expert Group (AQEG), 2019; Grigoratos & Martini, 2014; Wakeling, et al., 2018). Hagino et al. (2016) demonstrate that for disc-based systems, particle emissions have two peaks, with one occurring due to friction between the brake disc and pads during the braking event, and a subsequent peak during a separate event involving rotor rotation and acceleration. Hagino et al. (2016) conclude that this may be due to 'drag' where the brake pad is not retracted from the disc. Mathissen et al. (2019) reported that "off-brake-event" emissions contribute up to about 30% to the total brake PM_{10} emission. In contrast, a drum brake system was found by Hagino (2016) to only have one peak emissions event. Additionally, it was found by comparative studies, between disc and drum brakes, that disc brakes can emit ten times more particulate matter than drum brakes (Air Quality Expert Group (AQEG), 2019). Lower differences have been reported in a recently completed study by the CARB (unpublished data). While drum brakes are typically the reserve of heavy-duty vehicles or are applied in the rear axle of smaller passenger cars, for light-duty vehicles that employ disc-brake systems, positive piston (brake-pad) retraction on both sides of the brake disc has been recommended in the literature as a measure to reduce the second emission peak associated with brake 'drag' (Wakeling, et al., 2018). This can be achieved with dedicated callipers (zero-drag callipers); however, it is linked to higher overall cost of the brake system. At the same time, no studies demonstrating a reduction of PM_{10} emissions with these callipers are available in the literature. Very recently, the University of Darmstadt published a study which concluded that it possible to reduce or avoid off-brake emissions with mounted calliper by applying pad retraction; however, the avoidance of brake-off emissions does not lead in significant overall PM_{10} reduction over an entire cycle (Niemann 2021). Overall, this technology is not considered adequate to induce significant particle emission reductions. On the other hand, drum brakes mounted to the rear axle of certain vehicle categories (i.e., low- or medium-sized LDVs) may result to significant particle emission reduction with no additional cost and need for development or technological improvement. However, it should be pointed out that drum brakes are not appropriate for all vehicle categories (i.e., larger vehicles or SUVs) and cannot be applied as braking technology in the front axle for safety reasons.

The use of alternative materials for brake disc-pads is cited by a number of papers as a large determinant of brake wear material. In Europe, brake couples typically include grey cast iron discs and Low Steel (LS) or Low Metallic (LM) brake pads (Grigoratos 2021). Alternative discs and non-asbestos organic (NAO) pads have both been found to be more durable alternatives (Air Quality Expert Group (AQEG), 2019; Wakeling, et al., 2018). More specifically, NAO pads seem to emit 3-5 times lower PM_{10} and $PM_{2.5}$ compared to LS pads (Grigoratos 2021), while PN emissions of both materials have been found to be at the same levels. NAO pads were stated to be more expensive than LS formulated brake pads; however, the difference is counterbalanced when their duration expectancy is considered. NAO pads were also found in one study to exhibit higher per mass toxicity than LS pad wear that was considered to originate from the higher copper content of NAO pads compared to LS ones. However, this study employed pre-2014 NAO pads which are now considered outdated as a result of the Cu phase-out initiated in the USA (Gelofs-Nijland et al., 2019) for all pad types. Copper-free pads are being manufactured mostly to address relevant copper content regulations in USA (e.g., Nishimura et al. 2020). Taking into account the global character of the brake pads industry this regulation is expected to affect also other markets worldwide.

The use of alternative materials for the brake disc has also been discussed extensively. Ceramic and aluminium discs are already available in the market and provide a viable alternative to grey cast iron discs. Another widely applied solution is the so-called coated discs. Several studies have reported the potential of this type of discs to practically eliminate disc wear (Hesse et al. 2021). Some of these solutions are already available in the market, whereas there is a wide range of applications ready to be introduced (Eibl, 2021). However, special attention shall be paid to the type of materials used as coatings. In general, changes to the materials of the brakes will also have an impact on the toxicity of the emissions from brake wear and therefore the overall health impacts. Therefore, when looking to reduce emissions of particulate matter from brake wear emissions, it is important to consider the chemical profile of the emissions as well as the overall particle mass or number.

Alongside coated brake discs, regenerative braking was the technology most frequently cited by stakeholders to reduce brake wear emissions, in response to the 2nd targeted consultation. In principle, it is expected that more than 70% of the braking events during normal driving conditions in EVs will be covered by regenerative braking. However, no evidence regarding the quantification of the emissions reduction is available in the literature. It was suggested by two stakeholders that in comparison to conventional systems, regenerative braking could reduce particle emissions by 60-70%. So far, smaller reduction has been reported for the front brake system of a hybrid vehicle tested under the WLTP-Brake cycle (Agudelo et al. 2021). However, we could not locate further experimental evidence in the literature on the reduction of PM by regenerative braking. Augsburg and Hesse (2018) presented in the 48th PMP meeting two brake energy recuperation systems and their impact on particle wear. One of the systems coupled to NAO pads led up to 99% reduction in particle number over WLTC. However, respective reductions in particle mass were not mentioned in the paper. Different regenerative braking systems are and will be made available to the market, in terms of implementation technology and maximum power absorbance, depending on electrification powertrain. Hence, although it is certain that regenerative braking will play a significant role in decreasing future PM emissions, the extent of this reduction is currently impossible to specify with certainty.

The EC Horizon 2020 project titled ‘A Low Environmental Impact Brake System’ (LOWBRASYS), which aimed to demonstrate a new brake system capable of delivering a 50% reduction of micro and nanoparticle emission, identified key technology areas to achieve this that are similar to the areas explored above, including (1) novel material formulations for brake pads and discs, (2) optimised braking strategies, (3) technology to capture particles. Optimised braking strategies included a brake by wire system, which would distribute the brake force between the front and rear wheels to prevent transition temperatures from exceeding critical levels (Grigoratos, 2019). A series of other strategies (Predictive Efficiency Assistant (PEA), Adaptive Cruise Control (ACC), Car-to-X-Communication systems, etc.) have a good potential in reducing overall PM emissions from brakes (Guckeisen et al. 2018 – 47th PMP Meeting); however, no study up to now has quantified the potential reductions from these systems.

Particle filters and vacuum aspiration techniques have been recently recommended as solutions to significantly reduce brake PM emissions from motor vehicles (Mann-Hummel,2021; Tallano, 2021) and possible others that may not be publicly known because of commercial sensitivities. Recommended concepts encompass not only the first fitment market but also take into account the retrofit market (Bock et al. 2019). These systems are advertised to have filtration efficiency that can reach up to 80%; however, they have not been tested extensively and under all possible conditions and commercial implementations are still limited. Additional concerns include the dimensioning of such systems and the overall brake corner as well as the need for regular maintenance to keep the filtration efficiency at acceptable levels.

10.4.2 Tyre Wear Technologies

For tyres, the use of less harmful substances in manufacturing and increased use of tyre pressure monitoring systems have been suggested as part of a call for evidence regarding the reduction of tyre wear emissions (Defra; Department for Transport; Office for Low Emission Vehicles, 2019). However, Kole et al. (2017) identify what they term the “magic triangle” within tyre technology. This term represents the relationship between measures to control tyres’ rolling resistance, slip resistance and durability, stipulating that an attempt to improve the durability of a tyre by increasing its wear resistance might result in the deterioration of the tyre’s rolling and slip resistance. This might result in a subsequent negative impact on the safety and fuel consumption (and thus CO_2 emissions) of the vehicle overall.

As part of the 2nd targeted stakeholder consultation, two responses were received regarding technologies to reduce tyre wear emissions. These expert stakeholders identified that low rolling resistance tyre compounds and the adaption of the tyre air pressure by means of tyre pressure monitoring are the key technologies to reduce emissions. At this point it is important to mention that no standardised methodology for sampling and measuring tyre wear emissions exists. However, the EC recently mandated the development of a methodology for the measurement of tyres' abrasion rate. This method will allow to rate the tyres based on their performance taking into account the total material released in the environment. At a later stage, it is expected that the PMP group will examine the relationship between the abrasion rate of the tyres and their PM and PN emissions performance. The potential of the recommended emissions reduction solutions – as well as of others not considered in this report – could be evaluated once the methods are in place.

Within the literature, a relationship is found between vehicle weight and the subsequent emissions from tyre wear. As a result of this relationship, it is therefore assumed that as electric cars are heavier than their internal combustion engine counterparts, due to their battery pack, that they will have higher emissions from tyre wear as a result (Defra; Department for Transport; Office for Low Emission Vehicles, 2019). Up to now this effect has not been quantified in terms of PM_{10} and $PM_{2.5}$ emissions. However, as electric vehicle batteries develop, they are becoming lighter. Additionally, tyre wear due to braking events is expected to be reduced in EVs due to the use of regenerative braking allowing a significant reduction of the application of friction brakes.

10.5 Emission levels achievable

The currently best performing brake couples in the market in terms of emission behaviour include NAO pads and are considered to emit brake PM_{10} at the level of 4-6 mg km^{-1} $vehicle^{-1}$ ($PM_{2.5}$ being almost 30-40% of PM_{10} – Grigoratos 2021). There is a potential to further decrease these emissions with the application of already available different types of brake discs (i.e., carbon ceramic or/and aluminium) as well as with the application of coated brake discs which are expected to minimise disc wear. The latest might be an ideal solution for heavier LDVs such as SUVs which are expected to emit higher PM_{10} and $PM_{2.5}$. PM emissions can further reduce significantly (30-60%) if brake particle filters are considered. However, this technology is not yet considered mature for immediate large-scale application. Finally, the application of drum brakes in the rear axle of smaller LDVs is also considered a viable solution for reducing vehicle overall PM emissions. Drum brakes are already available in the market and commonly used in smaller and medium range LDVs. PN emissions (#/km) of all available brake systems in the market are expected to be lower than the current limit for exhaust emissions. However, the influence of individual extreme braking events to the overall PN concentration shall be evaluated.

Currently there is no information regarding improved emissions factors from tyres. A project (LEON-T) funded by DG-RTD with the aim of addressing the limitation of tyre wear emissions and providing some mechanistic insights is expected to start in June 2021. State-of-the-art tyre wear PM and PN emission factors both in the laboratory and on-road will be investigated in the project; however, results are not expected to be published earlier than 2022.

The EC has mandated the development of a standardised methodology for measuring the abrasion rates of tyres. This is overseen by DG-GROW and started its activities in June 2021. Potentially the project will be overseen by the PMP working group, with the path to potential UNECE regulation following a similar route to that of brake wear. As with brake wear developments over the past few years, the regulatory control of tyre wear will need to commence with the development of a standardised methodology for measurements. Future EC regulations aiming at reducing tyre wear will conceivably target the whole particle size range including microplastics, and not just the airborne fraction - thus increasing the measurement challenge. It is unlikely that a suitable tyre wear measurement methodology would be developed in the timeframe suitable for inclusion in EURO 7.

10.6 Costs of best available technologies

No specific research on control options and their costs for tyre wear were conducted in the framework of the current study. As earlier explained, more research is needed in the area of tyre/road interaction as well as measurement and sampling techniques before one develops a reference value and reduction scenarios for the future. As a general statement, as with tyre noise, one would expect that better material and tyre design will be required to achieve lower wear emissions. This will initially lead to higher costs, also including the R&D investment to develop these new tyres. However, incremental costs are expected to gradually drop, as such new tyres become part of the complete vehicle setup and manufactured in volume. Also, it is expected that the improvement of the tyres' wear performance will be realised through their overall improvement in view of possible microplastic emissions related regulations.

In terms of brake emission control technologies, a number of options have been earlier identified with the potential to decrease PM emissions. Table 10-1 presents a summary of the expected costs of the different options. These cost values have originated from exchange with experts during the stakeholder consultations, information stemming from the relevant work of the PMP group, and engineering judgment based on technology maturity and assessment. Costs refer to the average passenger car, obviously vehicle size, powertrain technology, and brand specifics may affect the quoted costs in different directions.

Table 10-1: Costs of brake wear control options

Technology	Incremental cost factors	Incremental Cost (€/vehicle)
Regenerative braking	Controller system, coupling with mechanical brakes (assuming at least MHEV is deployed on all vehicles)	200-300
Coated discs	Material and manufacturing (e.g., carbon/tungsten discs), assuming four discs per vehicle	200-650
NAO Pads	Material and processing costs to achieve low steel equivalent performance	7 - 10
PM Collection Devices	Design and new components required	150-300
Application of drum brakes in the rear axle	Nothing in particular – Technology already available and in use	-
Resizing of brake corner	Nothing in particular – Technology already available needs to be adapted to reduce energy dissipation and improve emissions behaviour	-

11 Findings on On-Board Diagnostics, On-Board Monitoring and Geofencing

11.1 Assessment of current OBD

Euro 6/VI final stages, RDE and OBD have successfully reduced tailpipe emissions. Focusing on the current OBD legislation, emission relevant subsystems are monitored. If a certain subsystem has a malfunction that results in not fulfilling the On-Board Threshold emission Limits (OTL), the MiL needs to be activated. The monitoring system needs to detect single emission relevant malfunctions within WLTP driving conditions. The WLTP covers a high share of the real driving behaviour (RDE) and so a malfunction will be detected within a high probability in normal use. In principle, the OBD system is attempting to infer first-order behaviour (i.e., increase in vehicle emissions) using second-order effects (i.e. proper functioning of individual emission control components). Within the current framework, the following specific weak points are detected:

- OBD only considers single-point failures
- Partial degradation of multiple components (high emitters with MIL-off) is not covered
- OBD certification is difficult to be proven by third parties
- There is a high cost and burden for OBD at Type Approval
- Tampering is still possible
- There are systems/occasions with emission impact, that are not monitored within current Euro 6 legislation (e.g., DPF regeneration frequency monitor)
- MiL reaction is complicated

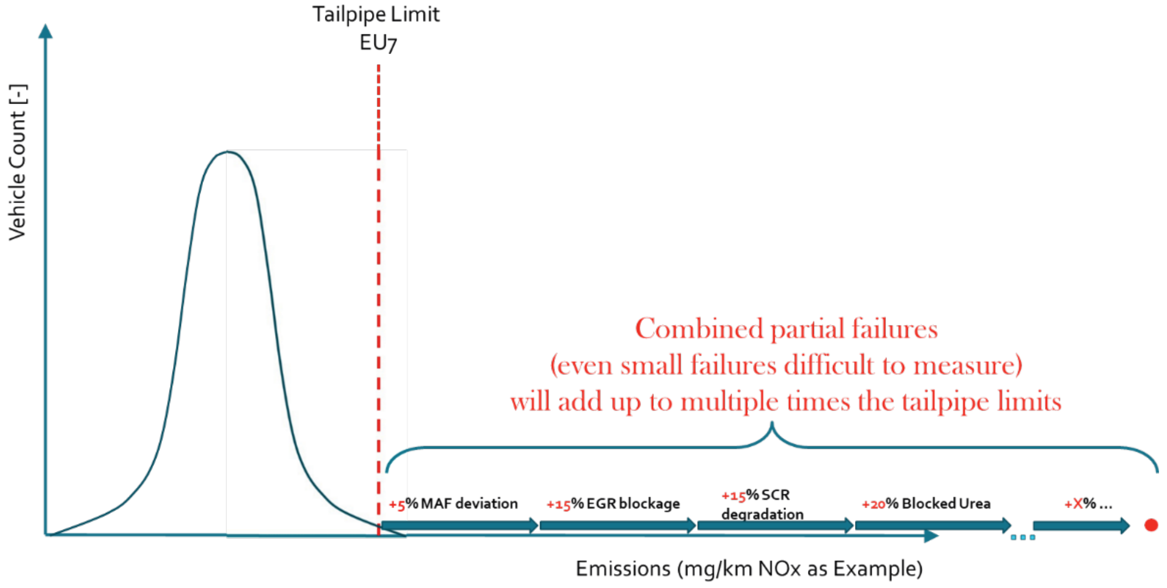


Figure 11-1: Partial failures effect on vehicle emissions

An example of OBD weakness is pointed in *Figure 11-1*. OBD considers only single-point failures monitoring the effectiveness of subsystems and not the emissions of the total system. If for two malfunctioned subsystems, the emission offset of each malfunction separately is below the OBD limit, it could be the case that the superposition of these malfunctions can lead to total tailpipe emissions higher than the tailpipe limit without MiL activation. Thus, partial degradation of multiple components can cumulatively cause emissions to exceed mandated tailpipe limits. OBD is also unable to detect other causes of tailpipe emission increase like malevolent tampering or defeat devices.

In such an environment, introducing direct and continuous on-board emission monitoring (OBM) seems to be a promising measure.

11.1.1 Key considerations for OBM

OBD is recommended to remain as a feature of vehicles to identify faults and facilitate repairs and maintenance, i.e., diagnostics. OBD testing will not be part of Type Approval and OBD compliance will only be declared during Type Approval. Also, OBD compliance can be checked during Market Surveillance i.e., if there is a malfunctioning component identified, the OBD system should identify it correctly in order to be repaired. In case the MiL is activated by the OBM system, the OBD systems need to identify possible failures in sub-systems and give guidance for repair. It is not possible to identify the root cause for every emission increase by an OBD system. Already today, fixing the shown OBD fault code is not always enough to solve the issue and the MiL activates again. To allow for pinpointing of issues with OBM, clear requirements and rules are needed:

- Is pinpointing in workshop possible with dedicated monitors?
- Can the system give more possible root causes with a probability?
- How many possible issues need to be pinpointed by the OBD system? Share of prober pinpointing.

Compliance with emission limits will be the main objective of OBM. Recent developments in the field of OBM in all regions i.e., EU with OBFCM (on board fuel consumption monitoring), US with REAL (real emissions assessment logging), China with Remote OBD, already demonstrate the significant possible benefits of the use of more advanced vehicle emission monitoring. For example, California (California Air Resources Board, 2018) and China (People’s Republic of China, Ministry of Ecology and Environment, 2018) have already adopted OBM regulations requiring heavy-duty vehicle (HDV) OBD systems to collect and store emissions data from the vehicle’s sensors.

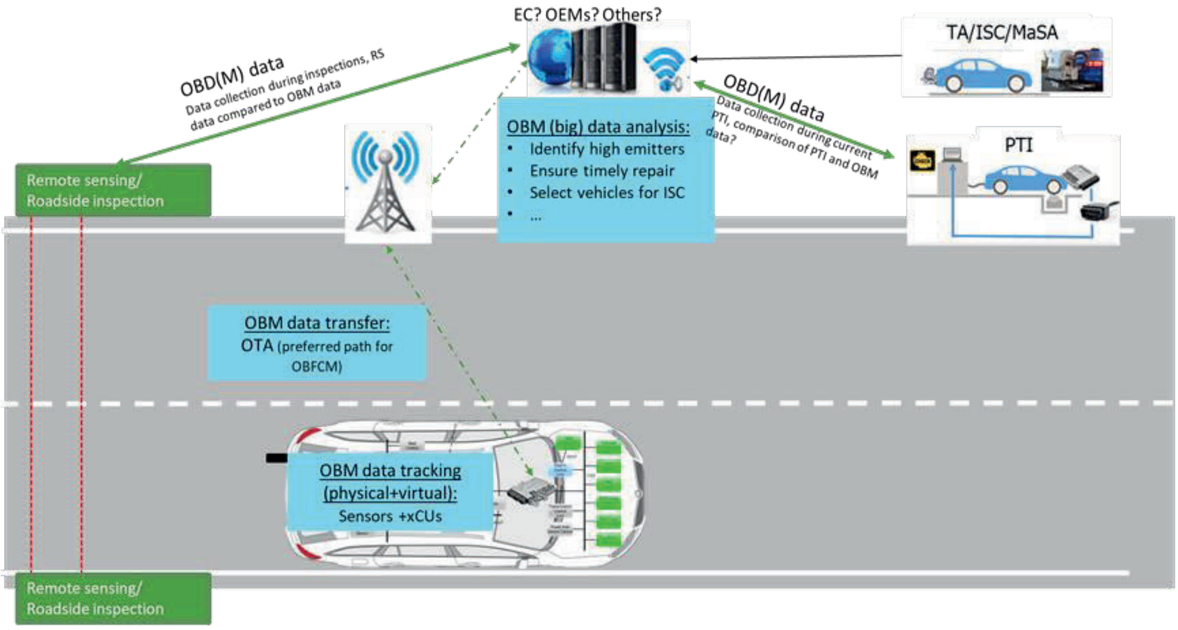


Figure 11-2: OBM as part of the future emissions compliance framework

In general, the OBM system can track emission-related data for each vehicle using physical sensors and calculation models. Via the on-board control units (i.e., engine and communication control units), these data can be available for either on-board or on-the-cloud data processing (Figure 11-2).

Data tracking on the vehicle

The tracking can be partially performed with the available on-board sensors and devices, but advanced sensors are needed for more comprehensive monitoring. As an example, monitoring of NOx emissions may be sufficiently and accurately performed by current on-board NOx sensors, but for particulate matter emission monitoring (either PM or PN), the current resistive sensors are efficient only for diesel engines, and therefore, new sensors must be developed for GPF monitoring or more accurate diesel monitoring. In the meantime, the OBM can build on the available OBD algorithms used as part of a model-based approach. Also, On-board anti-tampering security measures that are currently developed (e.g., DIAS H2020 project[42]) are necessary for the sensor data integrity. A detailed analysis of the technical feasibility of OBM sensors is presented in Section 11.2.

Data storage, access and transfer to the cloud

Regarding the data access, the current wired access to OBD data can be enhanced with remote access (e.g., Over the Air, OTA). Towards this direction, it is necessary to take advantage of the available or upcoming infrastructures and investigations in the field of sustainable mobility. Indicative examples are data collection solutions from OBFCM investigation, advanced and secure OBD methods from DIAS H2020 project, extended vehicles feature from ISO standards, OEMs applications for eco-friendlier driving etc. The data storage requirements are closely related to the necessary signals that need to the recommended policies for OBM. For all recommended policies analysed in section 11.3.2, two generic levels of data storage can be identified:

[42] DIAS: Diagnostic Anti-tampering Systems, H2020, www.dias-project.com

- **On-board data storage:** In general, it is considered the evolution of the current OBD targeting at the identification of high emissions and enforcement for repair. MiL activation is a key component on this level to inform the driver of the emission performance of the vehicle and enforce for repair.
- **On the cloud:** It is a new level introduced in OBM in addition to the on-board data storage. The main targets are the anti-tampering provisions (i.e., as described and currently investigated by the DIAS H2020 project) and the monitoring of the emission performance of vehicle types. Emission data will be available from the vehicle via an OTA approach, and new policies can be deployed using big data analysis methods. The necessary data to be transferred from OBM system are related to information for vehicle identifying, tailpipe gaseous and particulate emissions (based on sensors), exhaust flow and the necessary inputs for the evaluation of OBM trips validity to enable emissions compliance check. As regards the data transmission pathways, an extensive study is currently on-going for the OBFCM relevant data. Similar pathways can be used for OBM data (on-going evaluation from CLOVE). Finally, it is important to define how the OBM could be used. It is not the Commission who needs to act in a first place but the Member States (MS), which will need access to the OBM data. To this aim, two relative options were analysed by RDW in the relevant draft Impact Assessment report of the use and registration of OBM data (RDW, 2021):
    - Option A: Each MS creates the related IT infrastructure to collect data from vehicles circulating in their territory. The data would need to be shared with the GTAA.
    - Option B: Use of a common infrastructure, like EUCARIS, where the data are collected and stored in a central (or distributed) IT system and each MS/GTAA has access to the part of the data that is needed.

  Based on the conclusions of this study, Option B offers more advantages both in terms of functionalities and total cost.

For both levels, an important parameter is the interval (time or other) in which emissions will be obtained/evaluated for OBM purposes. An analysis based on second-by-second emission measurements is considered impractical at this stage due to the enormous data storage/transfer requirements and the high uncertainty of the exhaust sensors. Therefore, methods using average values are currently considered and analysed in the next section.

Data analysis

Possible methods to aggregate and analyse OBM data are:

- Accumulated tailpipe emissions over a distance or time window (interval)
- Binning method
- “Time above limit” method.

Accumulated tailpipe emissions over a distance or time window (interval)

In Figure 11-3, a NOx amperometric sensor was compared to reference equipment regarding cumulative tailpipe NOx emissions at 300 seconds and 5 km windows. The results are quite different between the two methods, but both end up in cumulative emissions deviation below ±50%. Greater deviations observed below NOx 20 mg/km, are related to exhaust pressure and NH_3 cross-sensitivities. Additionally, the sensor is not sensitive to emission “peaks” at the urban part causing, locally, underestimation of tailpipe emissions. In 300 second windows, this underestimation is emphasised. Inversely, the first 5 km window is approximately 30 minutes (the first urban part with very low average vehicle speed) hence, greater local deviations are partially mitigated (positive/negative deviations cancel each other out). This happens also in the whole RDE cycle where the NOx sensor deviates <10% from real tailpipe emissions (NOx ~30 mg/km).

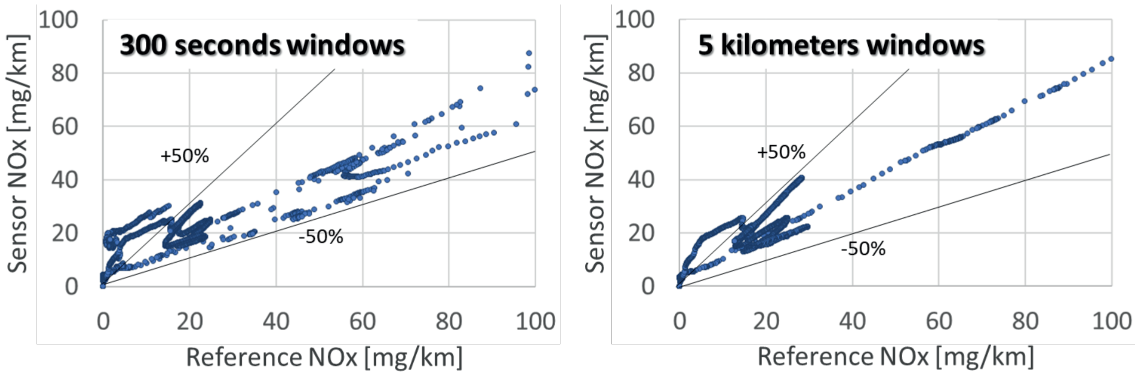


Figure 11-3: Example of data analysis, cumulative NOx emissions at time and distance windows, diesel RDE hot with new window every 1 second [43]

Binning method

In Figure 11-4, the instantaneous NOx emissions from an RDE hot cycle have been filtered and segmented into “bins” based on vehicle speed and power rate criteria. This method provides, in a direct way, the mass pollutant emissions but complexity is increased since final output (except BIN1) does not represent a continuous time interval or distance and even in the same binning category total time and distance are not constant among the outputs.

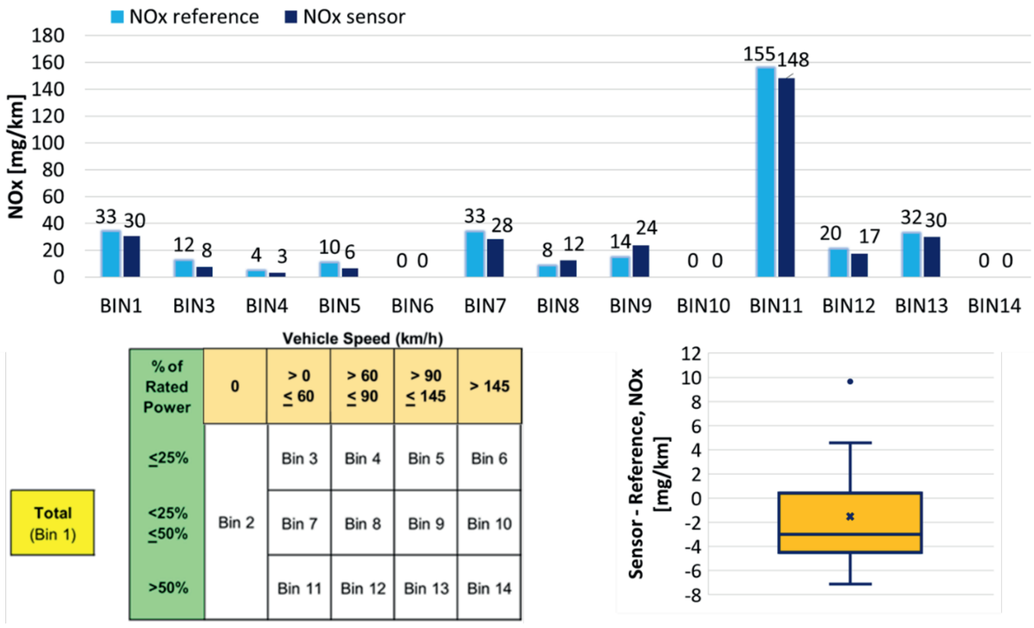


Figure 11-4: Binning based on power rate and vehicle speed, NOx emissions monitoring example, diesel RDE hot

“Time above limit” method

As seen at Figure 11-5, time above limit (TaL) can indicate the relative percentage of the cycle or trip in which emissions limit was exceeded. TaL could be a complementary indicator for emissions evaluation and supportive to OBM enabling conditions for compliance check or plausibility checks since it seems helpful for outlier detection.

[43] CLOVE OBM test campaign

Additionally, TaL could support emissions compliance check procedures after further calculations (e.g., integral of TaL in certain emissions levels) to derive a more direct magnitude in terms of mass pollutant emissions and physical meaning.

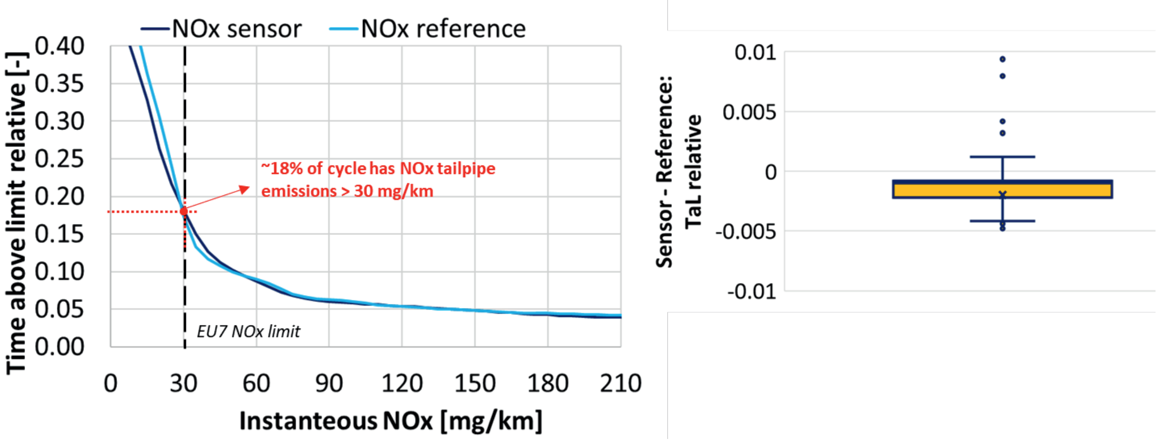


Figure 11-5: Time above Limit, NOx emissions monitoring example, diesel RDE hot

In general, to choose the most beneficial data analysis, every method suggested, should be thoroughly evaluated in terms of contribution on OBM components (sensors) accuracy and thus OBM system's tolerances, data transfer alleviation, complexity, etc. For the following analysis and the examined policies, the currently recommended minimum distance of 5 km will be used on most policies' examples.

11.2 Technical feasibility and characteristics of OBM sensors

The OBM system as part of the future emission compliance framework could operate supplementarily and beyond the current means for lifetime compliance and control of vehicle emissions. A key factor of the OBM approach is to identify the technical feasibility and requirements of the OBM system. To this aim, a detailed analysis of sensors is necessary to understand the short-term, mid-term and long-term capabilities for emission sensing. Current sensor availability is limited and mainly includes standalone sensors for NOx, PM (soot) and NH3. Additionally, there are a few prototype miniaturised sensors (e.g. for PM/PN) and sensor-based systems (or SEMS, micro-PEMS, nano-PEMS etc.) which combine emissions measurements (primarily based on standalone sensors) with additional OBD data and remote monitoring.

11.2.1 Basic sensors' characteristics

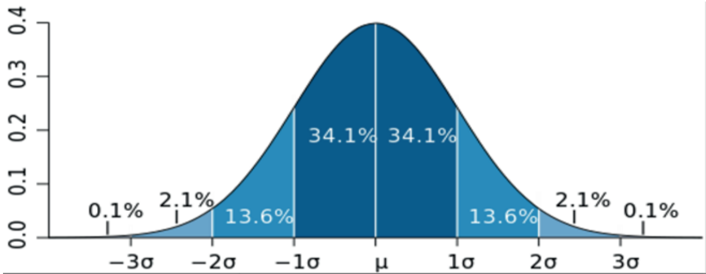
The main objective of this study is to define the pollutants that can be measured by on-board sensors at sufficient sensitivity and reasonable cost. For this purpose, several parameters were investigated:

- **Market availability and technical feasibility**: Both currently available but also under-development and close-to-the-market sensors are evaluated.
- **Operating limits (lower, upper, resolution)**: For example, current NH_3 sensors have a relatively low upper limit of 100 ppm. The investigation of NH_3-slip on SCR-equipped vehicles reveals significantly higher NH_3 peaks during dynamic driving conditions.

- **Sensitivities**: Current NOx sensor technology is sensitive to NH_3. Advanced signal processing makes it possible to reduce this effect. Also, the effects of exhaust temperature, pressure and velocity are assessed as cross-sensitivities.

- **Accuracy**: Sensitivity tolerances (also met as accuracy tolerances) over the range of secondary (non-raw) output constitute the sensors' element accuracy towards this magnitude (e.g., ±10% for NOx >100 ppm) and it is commonly measured at steady-state conditions. Element accuracy, by definition, depends only on the range of the component measured. Depending on pollutant concentration range, the form of a commonly used tolerance is ±x% >100 ppm and ±x ppm <100 ppm (e.g., NOx amperometric sensor). The latter implies that below 100 ppm accuracy is degrading at a relative basis. For example, if x = 10, the sensor's accuracy is ±10 ppm or ±100% at NOx concentrations of 10 ppm while at >100 ppm, it is ±10%. The current analysis focuses on low emissions depending on future legislation.

- **Sensor to sensor variability:** It refers to differences on sensors' parameters during the production process. For example, sensors are calibrated to succeed zero accuracy tolerances but in mass production, there are important deviations. Most relative information is available for NOx amperometric sensors. At these sensors' mass production, accuracy tolerances follow a normal distribution as seen in Figure 11-6. On average, sensors deviate ±0 ppm or 0 % for real NOx below or above 100 ppm, respectively. Regarding the mid-term available sensors, after 4 000 hours of operation, 99.7% of parts (±3 standard deviations from average) will deviate ~±5 ppm/%, while 95.4% of parts (±2 standard deviations from average) will deviate ±3.4 ppm/% (below/above NOx of 100 ppm). Usually, suppliers specify the final tolerances based on ±3-4 standard deviations from average ones. There are several strategies to improve "worst-case" accuracy tolerances and optimise calibration, such as software algorithms.



Element accuracy (NOx sensor example)	NOx ≥ 100 ppm	NOx < 100 ppm
μ (average)	0 %	0 ppm
σ (standard deviation)	2.5 % (aged part)	1.7-3 ppm (aged part)

Figure 11-6: Interval of accuracy definition, NOx amperometric sensor example[44]

- **Poisoning**: Ash is a serious concern for resistive PM sensors and electrochemical NOx sensors.

- **Readiness during cold start**: Many sensors (including NOx) are not operational for a few minutes after cold start to avoid thermal shock and damage. For NOx sensors, this period is also used to pump the oxygen out of the sensing cell. The current best available NOx sensors have reduced this "running-in" time down to 70 seconds.

[44] Standard deviation range refers to mid-term and currently available NOx sensor

- **Complexity (and cost and size)**: E.g. the currently developed prototype PN sensors (e.g., based on LII technique) may be too complex for automotive exhaust applications.
- **Calibration needs (and robustness)**: For PN/PM sensors, the exhaust particle size distribution seems to affect the calibration/correction needs of the sensors.
- **Sensor to sensor variability**: Differences during the production process cannot be neglected.
- **Sensor robustness and effect of environmental conditions**: High humidity, low ambient temperature or corrosive environment may affect the robustness of the sensor and long-term durability.
- **Software and communication interface**: CAN (Controller Area Network) is the default network for exhaust sensors. The security level and the anti-tampering robustness are also important parameters for investigation.
- **Signal exploitation (windows/binning, algorithms, Transfer function)**: E.g., windows of 60-600 s significantly optimise accuracy and correlation of PM electrostatic sensors.
- **Future improvements and applications**: Regarding aforementioned parameters.

The above characteristics for current and future sensors are summarised in Table 11-1. Additionally, these parameters can be classified at the three basic pillars of interest about sensors: accuracy (& readiness), lifetime, and range (Figure 11-7).

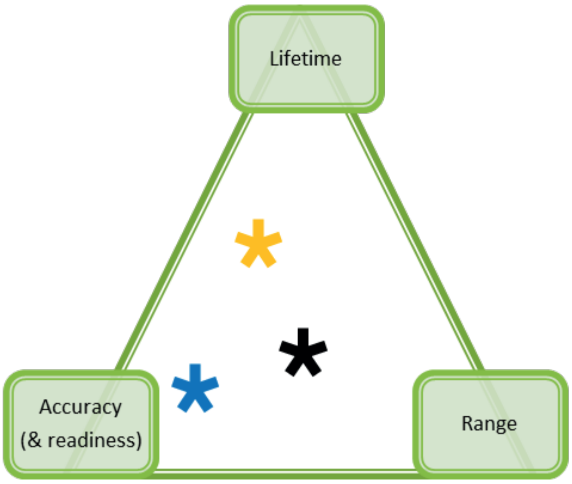


Figure 11-7: Sensors 3 pillars of interest. Blue, yellow and black star are OBM, future OBD and current OBD sensors, respectively

Due to OBD and market needs, the main focus is currently on an extended lifetime which is, however, significantly affected by readiness (i.e., low light-off or dew point can reduce durability). Concepts of different engine-out and tailpipe sensors to mitigate the need for a high measurement range and in this way achieve increased accuracy have been investigated by sensors' suppliers. For OBM, the focus is on low emissions and thus, sensors should be more accurate and sensitive in low emission levels. Correction functions and models can improve the performance. Considering all these facts, many suppliers are already taking steps forward and are developing improved sensing elements with high accuracy specifications at low emissions ranges. The above characteristics for current and future sensors are summarised in Table 11-1. Additionally, these parameters can be classified at the three basic pillars of interest about sensors: accuracy (& readiness), lifetime and range (Figure 11-7).

11.2.2 NOx sensors

NOx sensors are standard in today's Euro 6 diesel applications. They are used for controlling the de-NOx system (SCR and NOx storage catalyst) as well as for OBD. Most vehicles have more than one NOx sensor and they are already deriving the tailpipe emission mass flow within the control unit mainly for OBD reasons. The most common NOx sensor is the yttrium-stabilised zirconia (YSZ) electrochemical amperometric sensor. Vitesco, NGK/NTK, Bosch and Denso have commercially available sensors for automotive exhaust applications.

Currently available technology (amperometric): current and future generations (short/mid-term availability)

Amperometric NOx sensors have several electrochemical cells in adjacent chambers. Removal of O_2 is needed in this type of NOx sensor, and thus, it can also detect O_2 level. In the second cell, a reducing catalyst decomposes NOx into N_2 and O_2. Because of NH_3 oxidation to NO/NO_2, NOx sensors have NH_3 sensitivity which is one of the main causes of deviation from real NOx emissions. Measurement accuracy is different in low and high emission levels: ±10 ppm at 0-100 ppm and ±10% at >100 ppm. These are the worst tolerances based on sensor-to-sensor variability at mass sensor production and refer to ±3 standard deviations from the average tolerances which are close to ±0 ppm. In the near future, suppliers aim to minimise worst-case tolerances even to the half, that is ±5 from ±10 ppm. A possible strategy to succeed in this is a separate calibration for engine-out and tailpipe sensors. In this way, accuracy is optimised on the relevant NOx emission range. The long-term durability target for tailpipe sensors is 10 000 hours (short/mid-term is 6 000 hours). NH_3 sensitivity is expressed as an offset on sensor signal (+105-115% for 0-100 ppm NOx, NH_3). Thus, it can be effectively corrected with reliable NH_3 emissions input or with the appropriate physical-based algorithms (for petrol applications). Furthermore, exhaust gas flow cross-sensitivity can cause up to +10 mg/km offset from real NOx emissions, but better calibration and integrated correction algorithms are expected to tackle this effect. Cold start monitoring can be realised since upcoming NOx sensors generations are expected to be dew-point free, mitigating running-in time (time until sensor can measure) to 30-100 seconds. Also, sensors are already showing good accuracy and correlation with reference equipment even at cold conditions (0-100°C).

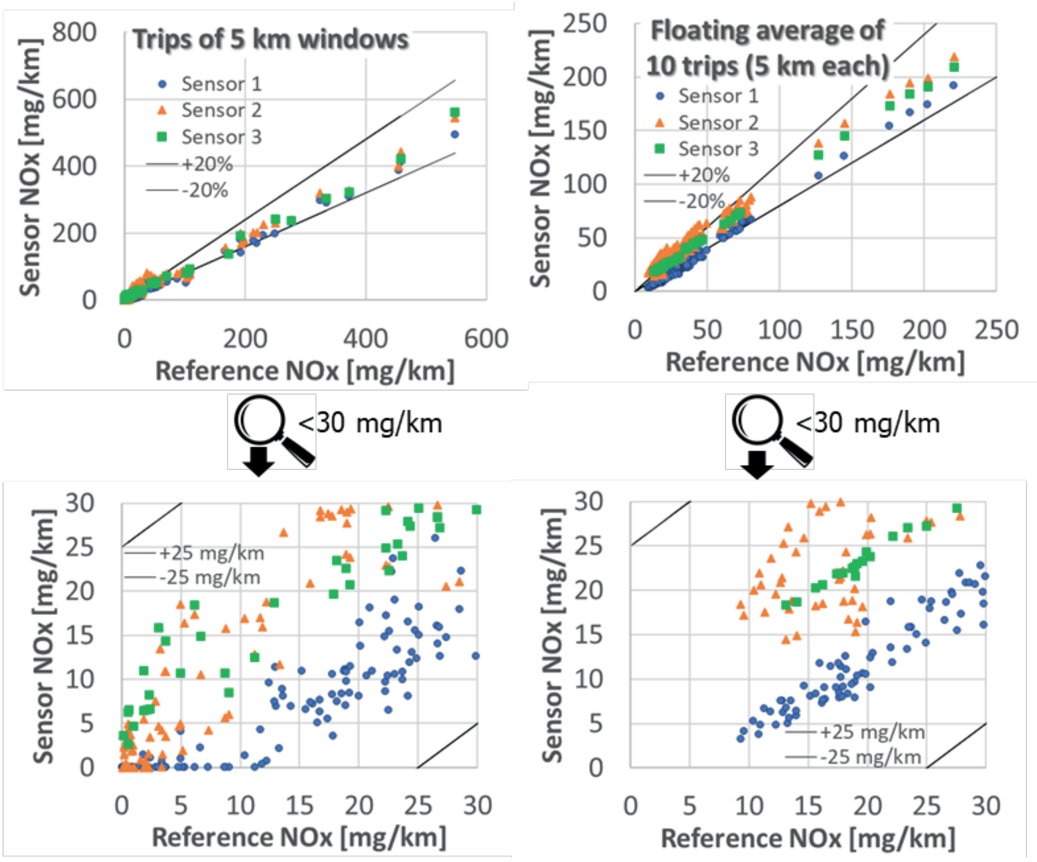


Figure 11-8: NOx amperometric sensor's accuracy regarding cumulative NOx emissions at distance windows (17 RDE & WLTC cycles, >150 trips)45

In Figure 11-8, NOx sensor results are presented for the recommended OBM signal processing methodology of 5 km trips and use of floating average of 10 trips. The following results refer to the best available technology for NOx sensors including next generation prototypes. The sensors belong to the 99.7% of mass production (±3 standard deviations from average) with tolerances within or better than ±5 ppm for NOx concentrations below 100 ppm. Also, a certain strategy was followed at testing to mitigate NH_3 cross-sensitivity effect (e.g., use of ASC). Nevertheless, to estimate the final results, NH_3 emissions as measured from NH_3 reference instrument were subtracted from NOx sensor's signal on cumulative basis (trip by trip). At NOx cumulative emissions <100 mg/km and independently of cold or hot conditions, the NOx sensor's deviation is <±25 mg/km for all the single 5 km trips. Deviations >±15 mg/km observed (~5% of single trips) can be attributed to cross-sensitivities encountered (e.g., exhaust gas temperature, flow, and pressure effect) and the failure of the relative correction algorithms to compensate them. Most of these deviations are minimised after applying floating average while the remaining ones are mostly related to sensors' accuracy tolerances. Sensor 3 (green squares) indicates <±1 ppm accuracy tolerances (for NOx<50 ppm) and thus it is representable of the average sensor of the mass production. After floating average of 10 trips, Sensor 3 deviates from real NOx emissions <±5 mg/km or <±20% for all cases independently of emissions level. If only trips with NOx emissions <30 mg/km are considered, the linear correlation is also improved when floating average is applied. Indicatively for Sensor 3, coefficient of determination R^2 increases from ~0.90 to 0.97.

[45]CLOVE OBM test campaign

Future developments (long-term availability)

Apart from improved generations of current amperometric sensors, new concepts are likely to be introduced (in the long-term) aiming at simultaneous NOx and NH_3 emission monitoring (Multigas sensors) or at alternative sensing technologies. The simplest approach for a Multigas sensor is the addition of a mixed-potential sensing electrode on the amperometric sensor probe. However, concerns have been raised regarding the feasibility of such a sensor due to durability issues related to mixed potential electrodes sensitivity to deterioration effects (mainly poisoning effects, change of diffusion and catalytically effects). For this reason, some suppliers have postponed or cancelled development of these sensors and instead they aim to utilise amperometric sensor NH_3 sensitivity and monitor both NOx and NH_3 emissions based on physical algorithms (currently addressed only to petrol applications).

In terms of different technologies, impedometric zirconia-based sensor developed by EmiSense (Khalek, 2019) and Carit/CPK Automotive (Bleicker, 2019), can be operated in two different modes, a dosimeter mode (ppb NOx range) and a gas sensor mode (ppm NOx range), by controlling the operating temperature of the storage material. This sensor is potentially suitable for ultra-low NOx concentrations and can act as a Multigas sensor by sweeping frequencies (i.e., from 1Hz to 100kHz) to characterise reaction peaks of a variety of gas species, a well-known method of impedance spectroscopy.

Some of the potential advantages of impedometric compared to amperometric NOx sensor are:

- Potentially suitable for ultra-low NOx: accuracy of ±10% at 5 ppm (for operational temperature of 350^{o}C)
- Simpler element: lower cost
- Larger signal: digital/time-domain/microamps vs. analog/nanoamps
- Faster response: chemical kinetics, not diffusion limited
- Ability to resolve multiple gas species simultaneously (NO, NO_2, O_2, NH_3 and HC).

Field-effect transistor-based (FET) sensors (mainly SiC-based) are also under development for NOx and NH_3 measurements. Initially, they were developed for environmental and industrial applications, but there are a few attempts to develop prototypes also for automotive applications. SenSiC seems to be the most advanced in this field. To eliminate the ammonia sensitivity and other disadvantages of the amperometric YSZ sensor technology, metal oxide and potentiostatic electrochemical NOx sensors have been recommended. Apart from NOx emissions monitoring, they could be used in combination with commercial (amperometric) NOx sensor to indirectly estimate the NH_3 emissions from the difference of the two sensors' signals, since these sensors are insensitive to NH_3.

In the following example, a prototype potentiostatic sensor was tested in petrol vehicles, measuring NO and showing no NH_3 cross-sensitivity (Tanaka, et al., 2020). A state-of-the-art NOx amperometric sensor was also installed. As already explained, the latter shows great cross-sensitivity to NH_3, thus apart from NOx, NH_3 tailpipe emissions could be estimated as the difference between the two sensors signals. Fourier-transform infrared spectroscopy (FTIR) and laser-based (Laser) measurement systems were used as reference. As seen at Figure 11-9, potentiostatic sensor followed the trend of reference (FTIR) NO concentration while amperometric showed some additional peaks mostly related to NH_3 cross-sensitivity. NH_3 was emitted under the acceleration and engine start conditions and its measurement was qualitatively the same for the two sensors and the reference organs (FTIR and Laser).

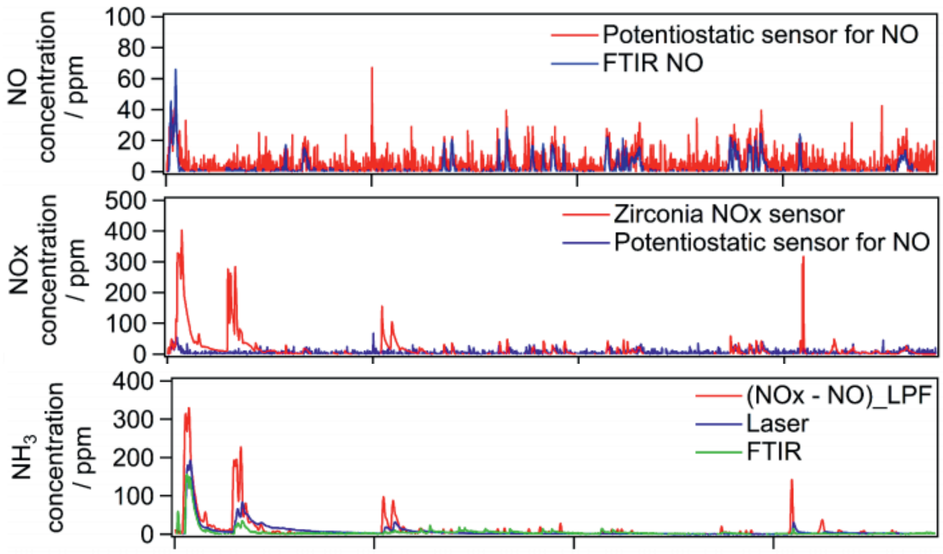


Figure 11-9: Potentiostatic and amperometric (zirconia) NOx sensors results at petrol engine tests (WLTC example)

11.2.3 NH_3 sensors

Delphi (first patent) and ECM (based on Delphi element) NH_3 sensors are the only available sensors designed for engine applications.

Currently available technology (mixed potential): current and future generations (short/mid-term availability)

Delphi's sensor was introduced in 2010 and was designed for the OBD of diesel engines for NOx reduction control. It is based on a mixed potential technology and consists of an electrochemical cell where solid oxide electrolyte ionises oxygen and carries oxygen ions to the other side of the oxide layer where the ions reduce NH_3 to N_2 and H_2O. In this reaction electromotive force (EMF) is formed and it is proportional to NH_3 concentration. The operation of the sensor and the known cross-interferences with H_2O, O_2, SO_2 and NO_2 are reported by (Wang, et al., 2009). According to this study the cross-interference of O_2 and H_2O are opposite to each other and therefore the sensor is partly self-compensating in that respect. NO_2 and SO_2 interferences are insignificant for SCR applications (where no NO_2 is present after SCR) and with automotive fuels (where the sulphur content of the fuel is negligible). In addition, the sensor has NO_2 compensation integrated based on NO_2 concentration information gained from the built-in NO_2 electrochemical cell into the existing NH_3 sensor device. Finally, there is also cross-sensitivity to CO (i.e., 40-200 ppm CO appears as 1 ppm NH_3). This is not an issue though when the sensor is installed downstream of an SCR catalyst where the CO levels are negligible under normal operation for diesel vehicles.

The performance of the mixed-potential sensor is characterised by nominal accuracy of ±5 ppm at 10 ppm NH_3, response time T_{60} = 3 s and T_{90} = 5 s, and durability of 5,000 hrs / 250,000 km. Operational temperature is 200-450°C and thus, operation during cold conditions is not possible (high light-off duration).

A mixed-potential NH_3 sensor's signal is also influenced by exhaust gas characteristics and components. An advanced correction algorithm can improve the accuracy. The necessary inputs to correct NH_3 sensor basic output (=NH_3 EMF) are O_2, NO_2, NOx, and exhaust gas temperature, flow, and pressure. Even if the uncertainty due to these corrections are excluded and assuming NH_3 ±5 ppm maximum deviation from reference, the final cumulative deviation is in order of ±5-10 mg/km, which is in the order of the future possible limit of 10 mg/km for LDVs. Thus, sensor accuracy is poor and an important issue at low NH_3 emissions (order of 10 ppm). An important concern for these sensors remains the poisoning by silicon, engine oil deposit, and long-chain hydrocarbons (unburned diesel fuel for example). The latter has been observed in some cold start situations before DOC reaches operational temperature.

Recent research (Wang, et al., 2018) concludes that after the introduction of well-dispersed Au nanoparticles into a $CeVO_4$ sensing electrode by a simple immersion method, the sensing performances of the sensor are dramatically improved while NO_2 up to 500 ppm cross-interference can be considered negligible. Silicon and engine deposit poisoning are also tackled by adding anti-poisoning coating layers. Protecting layers are already used and are continuously optimised in terms of poison, thermal and aging robustness. Compensation algorithms are also in continuous optimisation to increase sensors' accuracy.

Also, for better understanding and potential improvements of mixed-potential technology, sensor models are developed. A recent example is a finite element model (FEM) developed to elucidate the mechanisms behind mixed potential formation in mixtures or by varying the electrode configuration (Ritter, et al., 2019). FEM validates that the assumed mechanisms regarding the competing reactions at the electrode and heterogeneous catalysis are correct and can hereafter be described with numerical values. However, it is shown that at certain electrode configuration and operating points (low NH_3 concentrations), the simplified mixed-potential theory has its limits since it does not explain the measured signal, while FEM describes these cases with high accuracy.

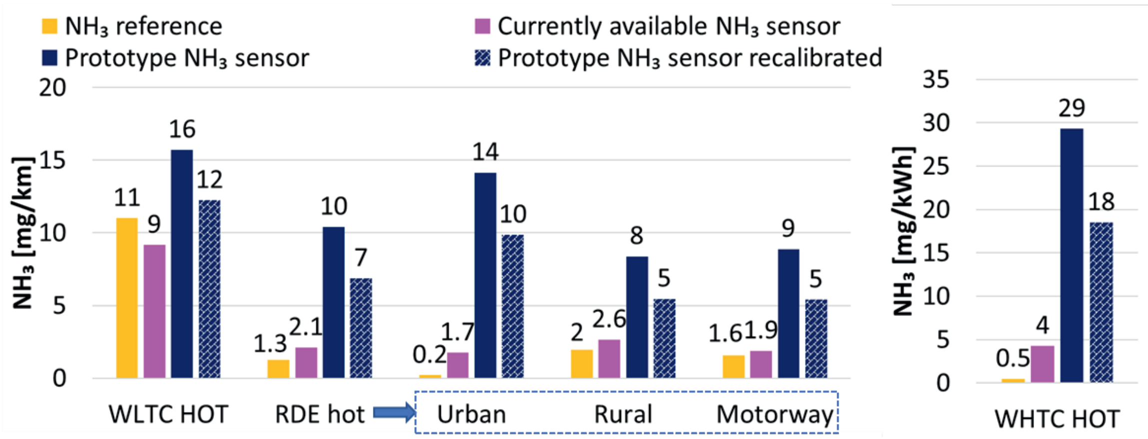


Figure 11-10: Prototype and currently available mixed-potential NH_3 sensors evaluation (transient results at diesel engine)[46]

A prototype and a currently available mixed-potential NH_3 sensor were available and tested on the OBM sensors campaign (Figure 11-10) at a diesel engine bench. The prototype sensor was not calibrated for ultra-low NH_3 emissions. After recalibration based on steady-state tests with NH_3<100 ppm, the cumulative deviation was reduced by 2-5 mg/km and 11 mg/kWh for LDV and HDV cycles, respectively. Intense signal noise was observed probably due to exhaust flow/pressure cross-sensitivity. Exhaust flow cross-sensitivity was significant mostly when low NH_3 concentrations and high exhaust flow levels/fluctuations were combined. This combination was more frequent at RDE urban and WHTC cycle and in turn deviation from reference was greater for both sensors. Nevertheless, for currently available NH_3 sensor cumulative deviation was below ±2 mg/km at 0-10 mg/km NH_3 tailpipe emissions. Sensors were also tested at cold conditions (first 30' of RDE cold cycle with exhaust gas temperature from 20°C to 70°C (55°C on average)) to check the cold start readiness. The prototype sensor was able to record NH3 concertation after 35 seconds, in

[46] CLOVE OBM test campaign

contrast with the currently available NH3 sensor which could not record before several minutes had passed and dew point (~200oC) was reached.

Future developments

The main future development could be a Multigas sensor:

- NH_3/NO_2 Sensor - Mixed potential (Not in Market)
- Oxygen Sensor + Mixed potential NH_3 (Not in Market)
- NOx Sensor + NH_3 Mixed potential (Not in Market)
- NOx Sensor + NH_3 oxidation/diffusion (Not in Market)
- NOx Sensor + NH_3-NO_2 Mixed potential (Not in Market)

Similar to the discussion for NOx Multigas sensors, the development of such sensors has either stopped or patent-based assessments are on-going.

As regards the mixed-potential technology, protecting layers for further optimisation in terms of poisoning, thermal and ageing robustness and sensor models (e.g., finite element model) are investigated as a basis for potential improvements. The main improvements of potential future mixed-potential sensors (this statement does not imply their future availability in the market nor the specific functions these sensors may have) are:

- Tighter Accuracy
- Faster Response Time
- Faster Light Off
- Thermal Shock Protection
- Increased Warranty Mileage

Recently, concerns have been raised for the accuracy and durability of the sensor and in particular, the signal deterioration of the sensor after only a few years of normal operation (this is currently under investigation and more detailed data will be available in the near future). The prototype developments of the mixed-potential technology by two suppliers have been stopped due to these concerns.

Despite the emerging lack of efficient measures to meet the required technical performance of the mixed-potential technology, there are alternative proposals to achieve NH_3 monitoring:

- Via model-based system functions: an advanced NOx/NH_3 separation algorithm and use of the NH_3 cross-sensitivity of the NOx amperometric sensor could achieve the same performance as a NH_3 mixed potential sensor
- Via a composite NOx + NH_3 emission monitoring: this can be realised by utilising the existing NOx amperometric sensor and its known sensitivity to NH_3. The simplicity and accuracy of this method will be high.
- Via new sensing technologies: As also aforementioned in NOx sensors future development, a Swedish company (SenSiC) also manufactures NOx/NH_3 sensors for hot gas measurements following the Field-effect transistor principle. Sensor is primarily designed for powerplant applications and currently the maximum operational temperature is 300°C.

11.2.4 PM/PN Sensors

Primarily resistive PM sensors (and secondarily advanced delta-pressure sensors) are currently used by automotive manufacturers in diesel vehicles to conform with the latest Euro 6-2 OBD legislation in terms of PM emissions.

Currently available technology (resistive)

Bosch, Stoneridge and Denso (under development) are currently providing resistive sensors for automotive applications. The sensing element of a resistive sensor consists of a ceramic plate from aluminium oxide (Al_2O_3) or zirconium dioxide (ZrO_2). Two platinum electrodes are mounted on the ceramic plate at a specific distance between them. When the sensor is clean from soot, the electrical resistance between these two electrodes is infinite. During the sensing mode, soot deposits and accumulates between the electrodes and gradually decreases the resistance. The measured value could be the voltage in a steady-current circuit or the current in a steady-voltage circuit. Above a specific value of the resistance, the regeneration mode of the sensor is activated to clean the soot deposits, increasing the value of resistance to infinite. The critical measurable quantity is the duration of the sensor's accumulation event which is called response time. With the aid of an OBD model and algorithms, the cumulative or average soot emissions during the sensor accumulation period can be calculated. The non-continuous operation due to the regeneration events, the insufficient sensitivity at low PM concentration levels, the lack of real-time output of PM concentration and the cross-sensitivity issues are limiting the potential of using resistive sensors for future on-vehicle measurements.

Future developments

A superior to the resistive PM sensor technology is used by EmiSense in the electrostatic sensor. Nevertheless, this technology is not currently used by the automotive industry due to the relatively high cost and the lack of regulatory requirements for more sensitive sensors. EmiSense, Continental and Honeywell have developed, or evolved sensors based on the electrostatic principle. The EmiSense sensor seems to have the most highly evolved design consisting of two coaxial electrodes protected by an optimised sensor tip. The principle of operation is to separate the positive and negative particles onto two electrodes, create dendrites of particles in each electrode that carry an amplified charge and afterwards measure the produced current from the electrically induced mobility created by the bouncing of agglomerates between the two electrodes. Owing to the high amplification gained by charge accumulation on the agglomerates (2-3 order of magnitude higher than the natural charge) the insulators and amplifiers of the sensor are simple and low-cost. The measured current is well correlated to PM. Correlation to PN has not been validated yet. Also, cross-sensitivity to exhaust flow was investigated: high flow increases the drag force of the dendrites and tilts them away from the opposite electrode without significant fragmentation. This phenomenon creates a quiescent period with artefacts on the sensor signal. Low concentration can deteriorate this phenomenon. Also, contrary to the resistive sensors, cross-sensitivity to ash is not a significant issue for the lifetime of the sensor.

Currently, there is only one commercial electrostatic design available mainly focused on high PM concentrations and heavy-duty diesel engines. The sensor has a very good trend when compared to the PM reference equipment. Regarding the correlation, it can be drastically increased using windows averaging for a certain time (50, 100, 500 sec) or for the whole legislative cycle. The higher the window time average the better correlation the sensor has with the reference equipment. However, this method reduces the real-time keen advantage over resistive technology. Another constraint is that the amplification phenomenon, which is the main reason for a simple and low-cost device, ceases for particles below 40nm (Bilby, et al., 2016) . Furthermore, the current design does not have a linear correlation with the reference equipment for soot concentrations lower than 1 mg/m^3. This is highly observable in low emission cycles or hybrid vehicle testing. The relative error between the sensor and the reference laboratory equipment (Micro Soot Sensor, MSS) is higher at lower flux and concentration values. However, a highly dynamic transient cycle could impact the sample flow extraction into the sensor thereby resulting in higher variability and a weaker relationship with reference measurements. Also, this technology is not directly measuring one of the PM or PN concentrations and a transfer function is needed. A simple example of a 'transfer function' is a linear correction of the electrostatic sensor using all the experimental data available. Another data analysis approach of the electrostatic sensor's signal is the application of a 5 km distance window average, similarly to time averaging. This method reduces the effect of transient phenomena on the sensor's signal and results in a good correlation with the reference equipment. Utilising this data analysis with a more sophisticated transfer function could be a possible accurate process for on board PM/PN emission monitoring.

For the electrostatic operating principle, a better understanding of the mechanisms that produce the sensor's signal, parallel with a physical model of the sensor could lead to developing an appropriate transfer function that would minimise the optimum averaging window. Furthermore, as the sensor is cycle -and engine technology- dependent, different designs, decreasing the gap between the two electrodes or applying a different voltage between the two electrodes could increase the sensitivity of the sensor at particles with lower size and charge and at lower soot concentrations (conditions existing in Petrol engines) meeting the requirements of future legislations.

The Diffusive Charge technology is mainly used as reference equipment and for PEMS applications. The operating principle is based on the electrical detection of aerosol by the calculation of the escaping current. A sheath airflow is ionised by the corona discharge phenomenon which later charges the aerosol particles. The ions that have not charged any particle are captured by an electron trap. The measured escaping current from the charged particles exiting the trap correlates to the particle concentration in the exhaust gas. It measures down to 10nm particle size and calculates both the particle mass and particle number concentration. With appropriate calibration, both particle mass and number concentrations can be calculated (Ntziachristos, et al., 2013) . New designs reveal the potential of creating a real-time in-situ sensor for OBM of vehicle emissions. This technology has the potential of detecting more particles than soot (like ash) based on its operating principle. The current concept consists of pressurised air provision and an external pump. This technology has the best correlation and trend with the PM and PN reference equipment. Furthermore, it calculates efficiently the cumulative particle emissions. However, this technology is mainly constrained by its cost and complexity. It has vulnerable electronics and significant insulation demands due to high voltage usage. Furthermore, the corona used for air ionisation has instabilities at high exhaust gas temperatures and suffers from corrosion. Regarding the cross-sensitivity and durability, more research should be done to have adequate results for a clear conclusion. Finally, the signal of the sensor is proportional to the particle surface area so indirect measurement of PN and PM using a transfer function is feasible. Regarding a more practical and cheaper OBM diffusion charge sensor, a pumpless prototype concept may solve the main constraints of this technology. Removing the need for pressurised air would drastically reduce the cost and the sensor complexity. Furthermore, it would be applicable to a huge variety of engine types without an additional system needed. On the other hand, a more sophisticated transfer function to compensate for the exhaust mass flow cross-sensitivity will be necessary.

Finally, optical PM/PN sensors benefit from the result of the interaction between the exhaust particles with a laser beam. The incident light can be scattered by a particle, and in parallel, a portion of its energy can be absorbed by the particle. The combination of both effects is extinction. Sensitive detectors are used in all cases to measure and quantify this interaction based on scattering, absorption or extinction. A plethora of laboratory PN/PM instruments are based on the optical method: Condensation Particle Counter (CPC), Photo-Acoustic Soot Sensor (PASS), opacity meters, spot-meters and aethalometers are typical examples. For on-board applications, only a few candidates could cope with the demands for low cost, compact dimensions, no need for calibration during lifecycle and accurate PN/PM measurement. At a mature research level, Johannes Kepler University Linz (JKU) has presented a high-power pulsed Laser-Induced Incandescence (LII) sensor based on light absorption (Zhang, et al., 2016) and Bosch GmbH a continuous wavelength LII (Kammerer & Purkl, 2019).

In the LII technique, the temperature of the particles is increased approximately to 4 000K just below the soot sublimation temperature due to particles interaction with the laser beam and the consequent light absorption. Because of the higher temperature, the particles radiate more strongly. This increase in radiation (incandescence) is the LII signal. Its peak is proportional to soot mass and is measured using collection optics and photodetectors. After being heated, the soot particles cool and the incandescence signal will decay with time. This decay time lasts approximately 200–500 ns depending on the size of the primary particles (excitation time=5–20 ns). From the measured LII signal and by application of energy transfer process models, one can obtain information about the mass fraction (Solid PM) and size distribution of the illuminated particles. Afterwards, the calculation of PN is feasible. On the other hand, in the BOSCH approach the PN particles are calculated based on the sensor peaks and by using an algorithm is possible to calculate the mass and size of each measured particle.

The drawbacks of LII technology are that a proof of concept is still needed, the electronics are sensitive, and the probe needs external cooling (e.g., by pressurised air) which is an issue for OBM applications. Also, concerns are raised about the signal drift due to the clogging of the optical window, but this has been addressed by delivering the laser beam and collecting the incandescent light through the same access. Thus, only one optical window is in contact with the soot in the tailpipe, and the high-power pulsed laser radiation continuously cleans it. Other constraints are, the background light from the exhaust pipe, the several optoelectronic components needed that have high degradation risk and the impact of vibrations on them is critical. Finally, the size resolution of particles detected (cut-off limit) must be low enough to fulfil the legislative requirements, and the clogging of the optical window should be addressed. All the upper constraints make it a great challenge to create an affordable and functional sensor and its development is currently stopped by the main development supplier.

11.2.5 Model-based OBM

To monitor emissions continuously, a simulation model running on the ECU is needed that predicts the tailpipe emissions from an emission concentration and an emission volume/mass flow. To improve the model, sensors are used to adapt the simulation model. The model could be adapted based on direct sensors that measure the mass flow or the emission concentration (possible today for NOx and NH_3 with limitations) or based on sensors like temperature, pressure, O_2 concentration, and PM emission. The simulation model also needs to estimate the tailpipe emissions levels during phases the sensor is not active, not fast enough or in case the sensor can only measure in intervals. Also, the simulation model is needed for antitampering and sensor monitoring. Finally, a simulation model can provide monitoring of other emissions like CO, THC, CH_4, N_2O, HCHO, NMOG for which no sensors for vehicle application are available today. Therefore, there are two basic proposals for model-based OBM:

1. Models until sensor readiness: The main targeted policy is the long-term monitoring of emission levels and the comparison with TA values (section 11.3.2). In this case, the contribution is expected to be significant due to high cold start emissions. In

case of identification of high-emitters no significant contribution is expected for "RDE-type" long trips (urban, rural, motorway) since MIL activation can be successful and timely without considering the first 60 seconds.

2. Model-based monitoring for non-measurable species: Main targeted policy is the identification of high emitters.

Both proposals can be based on monitoring of parameters that are known to have an impact on emissions (based on OBD and possibly active diagnosis) e.g., monitoring or proper operation of EGR, AdBlue injection, other EAT components. Additionally, preceding or following trips/cycles can be used to detect/confirm a deterioration.

The base setup of such an emission simulation model is:

- Mass flow model
  - Mass flow sensor based (MAF). Most LD Diesel engine have a MAF sensor
  - Filling model (intake manifold pressure and temperature based). Standard for petrol vehicles
- Engine-out emission model
  - Based on engine condition (ageing status), operation load point and engine boundary condition
- Catalyst efficiency model
  - Based on catalyst condition (ageing status), engine out emission, catalyst temperature

The most critical task is to model the engine and catalyst condition. An emission sensor can clearly improve this and therefore the emission monitoring. Without the emission sensor the engine/ catalyst condition needs to be derived based on OBD monitors in use today. Today's OBD monitors derive the part condition based on available sensors in limited predefined driving condition by comparing the measured signals with defined signals for new and aged parts. This approach is clearly limited in monitoring accuracy.

Nevertheless, the usage of models for replacing emission sensor signals or for providing data until sensor readiness has some significant limitations which should be carefully considered. A robust model accuracy can be achieved for a single vehicle only with known conditions of all components (e.g., thermal aging, catalyst poisoning). The mechanisms leading to a different condition of components (e.g., thermal aging, catalyst poisoning) and the corresponding increase of emissions are complex and diverse and any additional input to the model adds further uncertainty in the final output emissions. However, there is no robust and long-term investigation on this field yet and further analysis is needed.

An example for CO monitoring for a Diesel engine is provided below (at present, no CO sensors are available):

- Engine out and tailpipe mass flow modelling based on engine filling model and mass flow sensor. In case of low pressure EGR the tailpipe mass flow and the mass flow of DOC are different and must be considered.
- The CO engine-out emission are modelled based on:
  - Injector condition (OBD)
  - Modelled and measured air fuel ratio
  - Engine operation point as well as boundary condition (coolant & intake air temperature, etc.)
- Monitoring of DOC efficiency

  - In dedicated driving and DOC operation condition the CO and HC emission are artificially increased, and the conversion efficiency is checked based on the temperature increase over DOC
  - DOC efficiency model is adapted based on measured temperature increase
  - Here it is important that the monitoring is done at different DOC temperatures and reasonably constant driving conditions are present. DOC efficiency monitoring is not possible in every trip
  - Challenging is the measurement of the temperature and that CO, HC emission are also modelled

- Tailpipe emission modelling
  - DOC efficiency based on DOC operation point (temperature & space velocity) and monitoring stage
  - CO engine out emission model.

11.2.6 Future sensors for other species

Apart from simulation models, there are some efforts on research and development of CO_2, N_2O, CH_4 and HC sensors. To this aim, micro-electro-mechanical systems (MEMS) have been designed. Among others, MEMS include micromachined, electrically tuneable VTT's Fabry-Perot Interferometer (FPI) used in Vaisala's CARBOCAP® CO_2 sensor (VTT and Vaisala partnership), NDIR gas sensors (CO_2 and probably CO) based on tuneable Fabry-Perot filters, thermopiles, and thermal emitters and acoustic emission sensors.

Current sensor suppliers have also made investigations on sensors for other species. N_2O detection can be made by applying limiting current technology with YSZ based conductor. N_2O is decomposed to O_2 on the electrodes and electric current generated by O_{2}- pumping is detected. The main constraint is that N_2O thermal decomposition ($N_2O \rightarrow N_2 + 0.5O_2$) occurs over 500°C before being decomposed electrically on the electrode. Thus, it is difficult to operate a sensor below 500°C and impossible to detect N_2O because of its thermal instability. Limiting current technology can also be applied on CH_4 sensors but, in this case, with a proton (H+) conductor. CH_4 is decomposed to H+ on the electrode and electric current generated by H+ pumping is detected. The problem is that all other gases which include Hydrogen (e.g., other HCs, H_2O) are also decomposed and the sensor cannot recognise and detect CH_4 independently in the exhaust gas.

While a couple of principles to detect hydrocarbons are described in the literature, only a few papers are dealing with applications of HC sensors in the harsh automotive exhaust[47]. For such applications, a thermoelectric hydrocarbon sensor, which is based on the reaction enthalpy of the unburnt hydrocarbons, is investigated. The sensors measure the resulting temperature difference between a catalytically active and a catalytically inactive part of the sensor. Therefore, at least one thermocouple (connection of two conducting materials) must be applied on a sensor substrate to detect the temperature difference. Additionally, a heating element on the rear side of the sensor allows operating the sensor above the light-off temperature of the catalytically material. Exothermic oxidation of hydrocarbons leads to a temperature increase at the catalytically active part, which generates a thermo-voltage between both parts. This sensor response depends linearly on the HC concentration, shows a long-term stable signal, and fast response and recovery times (HC 0-2350 ppm, operating temperatures 550-650°C, gas test bench). The only measurements at the engine test bench reveal dependency to the air-fuel ratio along with different oxygen concentrations. In general, for a commercially available HC sensor, significant further investigation must be made.

[47] (Jaroslaw, 2017), (Sven, 2015), (WU & MICHELI, 2004), and (Sahner, et al., 2006)

11.2.7 Summary table for sensors' capabilities

In summary, there are no currently available sensors for other species apart from for NOx, PM/PN and NH_3. The technical solutions for other sensors are considered premature and there is very limited information and data to assess the technical feasibility of such sensors. The current status and future developments for all tailpipe sensors are summarised in Table 11-1 below.

Table 11-1: Summary of short/mid- and long-term capabilities of tailpipe sensors

Short/mid-term capabilities	Long-term capabilities

• **NOx:** Amperometric next generation sensors
• Dew-point" free + Water resistance
• **NH_3** (diesel): Mixed-potential next gen. sensor (available in the market but further assessment is needed). Utilisation of NOx sensor via separation algorithms or a composite NOx+ NH_3 monitoring are currently investigated
• **NH_3** (petrol): Utilise cross sensitivity of NOx sensor (λ<1)
• **PM(/PN)** (diesel): Based on advanced filter diagnostics → resistive next generation sensors
• **(PM/) PN** (petrol): Based on advanced filter diagnostics → pressure or temperature or OSC-based
• **$CO/HC/CH_4$:** Partially with model-based monitoring (further evaluation is needed)
	• **NOx, NH_3**: Improved NOx and NH_3 sensors:
	  ○ Accuracy: <±7 ppm or <± 7 %
	  ○ "Dew-point" free + Water resistance improvements for all sensors
	  ○ Reduced NH_3 cross-sensitivity
	  ○ Separate Engine-out and tailpipe sensors
	• **PM/PN:** Advanced sensor technologies (Resistive, Electrostatic, Diffusion Charge, Laser Induced Incandescence)
	• **$CO/HC/CH_4$, other species:** currently not developed but feasible with appropriate lead time

11.3 OBM implementation

As a consequence of the limited accuracy and availability of OBM sensors, OBM implementation can be divided into two phases: short/mid-term and long-term. The first phase can be introduced with EURO 7 regulation and the second phase should be introduced in a later stage after significant improvements and advancements (i.e., development of new sensors) occur.

All OBM use-cases or policies that are recommended below are addressed either to individual vehicles (to determine whether an individual vehicle complies with emission regulations) or to vehicle types.

11.3.1 Technical principles of OBM implementation

Quality of OBM system

The OBM system itself should be verified in terms of accuracy and integrity. This can be done in parallel to the emission certification and OBM-based emissions for the complete trip can be compared with PEMS values. The difference of the average emission for some trips needs to be below a certain accuracy target. The accuracy target is set for every emission component in a way that it could be reached with state-of-the-art sensors and that it ensures clean vehicles. The correct MiL activation in case of high emissions or malfunctions of some OBM sensors should be also checked. The latter is very important because the sensors are subject to deterioration effects, or the system could have been tampered with. Thus, the sensors need to be manipulated and checked if the system is realising the issue within an RDE trip. Nevertheless, the objective is to do this with a relatively low number of additional PEMS tests and the OEM should ensure the OBM components' quality with on-board diagnostics of the OBM system (mainly to detect tampering). Additionally, based on OBM data analysis, a sample of vehicles can also be checked during PTI or ISC procedures to ensure the OBM data reliability. However, this is the second step to ensure data quality. Firstly, it is important to identify typical data problems (e.g., missing or invalid values and develop effective algorithms before utilising them for any in-use check purpose. On an early-stage assessment of the implemented OBM systems in China (Zhao, et al., 2021) data cleansing algorithms have been used focusing on several key parameters necessary for monitoring in-use NOx emissions, including timestamp, speed, NOx exhaust concentration (i.e., post-SCR NOx concentration for SCR-equipped HDVs), fuel flow, engine speed and torque, and urea solution level. Figure 11-11 illustrates the process used to conduct the diagnosis of data integrity and quality for each individual vehicle.

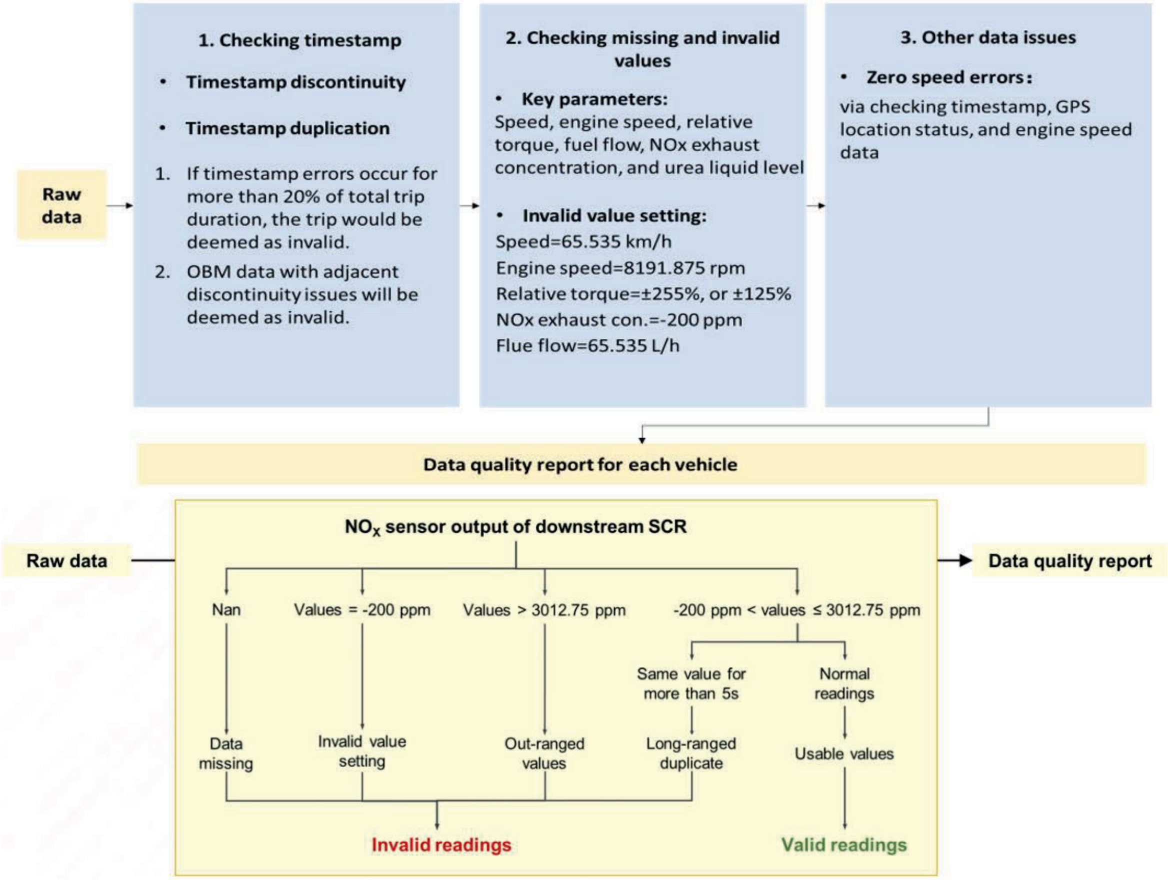


Figure 11-11: OBM data quality inspection procedure example

OBM tolerances

On-board emission monitoring has limited accuracy compared to PEMS or laboratory emission measurements due to the high uncertainty of the physical sensors and the simulation models that are needed. The uncertainty of the system is expressed as OBM tolerance and it will be considered when checking for emissions compliance (individual vehicles, Figure 11-12). OBM tolerances are estimated in the order of ±100-150% of the relative EURO 7 emissions limits. An OBM system with optimised next-generation NOx amperometric sensors can achieve a ±100% tolerance while NH_3 monitoring (based on mixed-potential sensors) and model-based monitoring (e.g., for CO) will need higher tolerances (>150%).

OBM enabling conditions

Emissions compliance monitoring will be realised under certain circumstances defined at emissions regulation. In turn, OBM system emissions outputs (trip or window) should be checked for validity in this sense. In addition to emissions legislation, OBM conditions based on sensors feasibility should be also applied. Based on emissions legislation, tailpipe emissions are monitored and conditions outside the boundaries are excluded. In addition, OBM enabling conditions based on sensors technical constrains should be also considered and applied. For example, emission values when sensors are not active (e.g., 30-100 s for NOx sensor light-off) can be based on OBM models but the higher uncertainty (OBM models are expected to be less accurate than the sensors) should be accounted via higher OBM tolerance. Some of the suggested criteria are briefly displayed below:

- Conditions beyond extended boundaries excluded (extreme ambient temperatures, too high elevation etc.) based on emission regulation

- Boundary OBM conditions to be covered by models (e.g., first 30 s after initial ignition where sensors are heated-up)
- Trip is above a minimum distance or work limit
- Trip is invalid after a vehicle's park time higher than ~4 days

The above criteria refer to a single OBM output (one trip or window). To normalise the effects present in single trips, the usage of floating average values is strongly recommended. For a floating average of the last 10 valid trips, additional validity criteria are needed:

- Valid averaging if trips are younger than ~4 weeks
- The averaged mileage of last 10 trips needs to be higher than ~100km
- Last trip before averaging should be valid (to avoid repeating averaging values)
- Number of valid OBM trips above 50% in last 10 trips

General OBM tasks

In addition to data tracking, transfer and analysis procedures, the OBM system should generally store (on ECU or elsewhere): the average emissions (current and lifetime), distances and emissions of last trips (4 weeks aged trips and all trips used for averaging), average particulate filter regeneration frequency, time and date with MiL active and date and mileage of OBM system's applied calibrations (self or external). All this information is vital for all policies that will be discussed, and they will give the appropriate feedback for continuous improvement of the OBM system functionality.

11.3.2 OBM policies

Policies for individual vehicles

Individual vehicle policies, which are only relevant for possible future introduction in the Roadworthiness context but not for Type Approval, are considering worst-case OBM system tolerances since the possibility of OBM false alerts and the following measures should be eliminated. Within the next table, all policies for individual vehicles are displayed.

Table 11-2: Individual vehicles policies: potential at phase 1 and 2 of OBM implementation

Policy addressed to:	**Policy**	**Phase 1 (short/mid-term): Introduction of EURO 7**	**Phase 2 (long-term): In a later stage**
		Based on improved generations of currently available pollutant sensors	Based on future pollutant sensors
 **Individual vehicles**	Identification of high-emitters and enforcement to repair	• **NOx, NH_3**: Sensor-based emission assessment • **PM(/PN)**: Based on advanced filter diagnostics • **CO/HC/CH_4:** Model-based monitoring (high tolerances)	• **NOx, NH_3**: Based on improved NOx and NH_3 sensors • **PM/PN:** Based on advanced sensors • **CO/HC /CH_4 + other species:** depends on sensor availability, currently not developed but feasible with appropriate lead time

	Tampering detection	• **NOx, NH_3, PM/PN:** On-board plausibility checks (too high or too low emissions) based on various sensors data and ECU models • **NOx:** Cloud-based detection *Note: Preventive security solutions (e.g. secure CAN) are prerequisites for sensor data integrity*	• Cloud-based tampering detection for all pollutants
	Improved roadworthiness inspections	• **NOx, NH_3, PM/PN**: - High emissions force the driver for emissions and OBM system check at next PTI - Partial alleviation of PTI (i.e., no emission testing for low emitters)	• Greater alleviation or total replacement of PTI/RSI emission testing procedures according to sensor availability and technical developments
	Long-term evaluation of emission performance	• **NOx and NH_3:** - emissions monitoring - Store on ECU or elsewhere: the average emissions, distances and emissions of last trips, average particulate filter regeneration frequency, time and date with MIL active and mileage of OBM system's applied calibrations	• **NOx, NH_3, PM/PN:** emission monitoring • **CO/HC/CH_4 + other species:** depends on sensor availability, currently not developed but feasible with appropriate lead time

**For all pollutants, the applicability of the current mini-PEMS, i-PEMS and SEMS for OBM phase 2 can be examined on the premise of further miniaturisation*

A vehicle's emissions compliance (over TA limit including OBM tolerance) is checked from OBM system and in case of non-compliance, further measures are taken (an example is explained below). This can be realised even at the initial OBM phase considering though, more relaxed tolerances. Also, plausibility checks based on various sensors data can be done to detect tampering. Anti-tampering potential can be greatly expanded at OBM phase 2 (e.g., by cloud-based anomaly detection). Furthermore, OBM can be complementary to the existing emission control procedures (i.e., emissions testing via PTI, RSI) for phase 1. However, OBM system is expected to replace these procedures partially or fully.

In the following text, a possible procedure for MiL activation is given. The MiL activation is done based on floating average emissions for a certain number of valid trips:

- Based on emissions legislation, tailpipe emissions are monitored and conditions outside the boundaries are excluded
- Every trip is 5 km (used as an example) and has been checked for validity (OBM enable conditions)
- If floating average emissions of a certain number of valid trips (e.g., 10 trips) are above the emissions limit including OBM tolerance, the driver is informed to check the emission system (MIL activation) with no further actions
- If the floating average emission goes again below the emissions limit (including OBM tolerance, MIL is deactivated
- Every MIL activation and the values of every trip with activated MIL are stored in the ECU with date, mileage and emission value
- Example for enforcement of repair:

- After 10 cold starts (note: this is only an indicative value) the enforcements start: (number of cold starts are shown in the dashboard)
- Full load limitation + maximum speed limitation (warning included)
- After further 5 cold starts:
    - Vehicle speed is limited to 10km/h
    - Reporting to the authorities (e.g., following OBFCM rules).

It should be emphasised that there are two separated stages:

1. MiL activation (identification of high emitter) and
2. Enforcement of repair (measures for high emitter).

Figure 11-12 shows an example of a possible emission behaviour for a moderate emission increase which could appear for catalyst ageing or a clogged valve. The emissions are constantly increasing, and the driver is informed by activating the MiL when the floating average minus the tolerance exceeds the emission limit. Also, the driver is informed on the number of cold starts that are still possible before the vehicle inducement (e.g., vehicle could not start anymore).

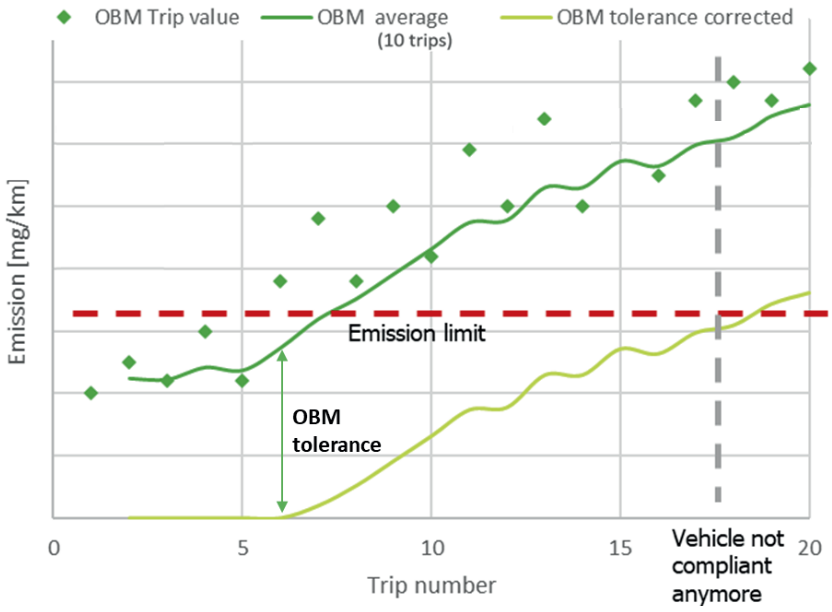


Figure 11-12: OBM of vehicle emissions compliance

Figure 11-13 shows the implementation of the aforementioned method for a sequence of RDE cycles simulated in an engine dyno. The AdBlue injection was controlled in a way to simulate a scenario of a period with low emissions followed by a period of high emissions (two MiL activations and one deactivation). The first MiL activation is triggered by the continuously increased emissions of the previous 10 trips (e.g., due to an emerging malfunction). In this case, the driver is informed to check the emission system with no further actions. MiL is deactivated when the floating average drops again below the limit. The second MiL activation is the result of constantly high emissions (close to the emission limit e.g., due to an aged system or a tampering attack). Since emissions are continuously increasing MiL remains active and the driver is informed on the number of cold starts that are still possible before the vehicle inducement (e.g., vehicle could not start anymore).

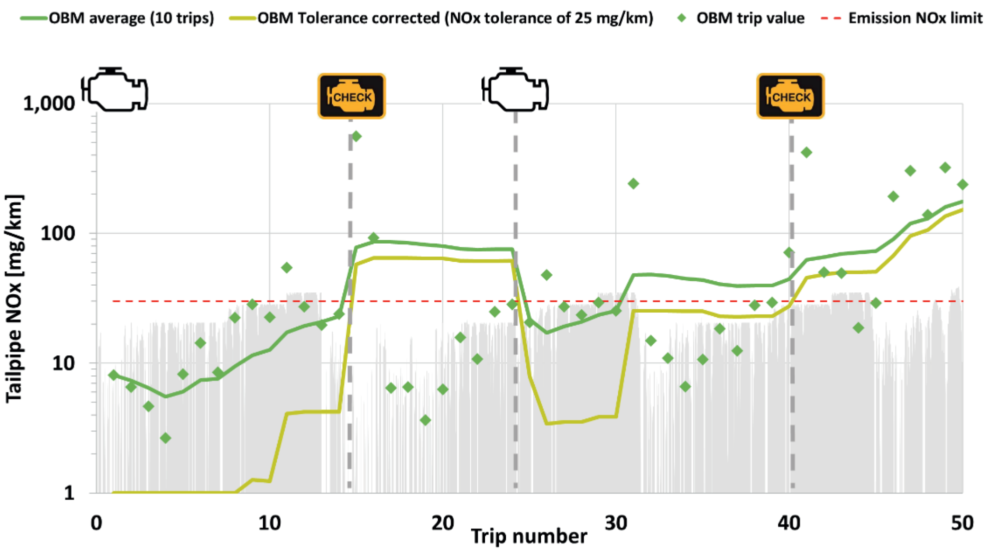


Figure 11-13: OBM of vehicle emissions compliance, NOx emissions example

Policies for vehicle types

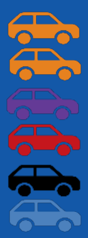
Emissions monitoring is not only addressed to individual vehicles but can be expanded to vehicle types. This is the application that is relevant for what concerns type approval framework, for ISC or MaS compliance checking.

From the initial OBM phase, on a fleet-wide basis, OBM data allow the evaluation of emissions performance (i.e., fleet average emissions, high emitters) categorised by region, country, vehicle family, etc. Vehicle types with increased emissions and potentially individual vehicles with very high emissions due to tampering will be identified after statistical evaluation of vehicles' OBM data off-board. Already, recent research claims that tailpipe NOx emissions can be determined based on on-board NOx sensor signals with good accuracy (Montes, 2018), (Shaojun, et al., 2020). OBM system reliability on a fleet basis is greatly improved compared to individual vehicle monitoring of emissions since data gathered are from a high number of sensors thus worst-case uncertainties (e.g., due to deviation from sensors' mass production) are normalised or can be removed. The potential benefit increases by using a decision function to separate outliers due to aggressive driving, ultra-short trips, etc., so that the final output will be a fleet emission performance evaluation regardless of boundary and driving conditions. In addition, type/family-based emission compliance will be available for all feasible to measure pollutants (NOx and NH_3, PM/PN probably at the second OBM phase). Additionally, based on individual tampered vehicles detection by OBM system, further analysis and conclusions can be made addressing vehicle types. For example, the fact that many of the same vehicle type are tampered with, provides indication that the antitampering measures required by the OEMs have not been applied correctly.

Some more of the outcome benefits are ISC/MaS pre-selection and valuable data and experience for a future revision of emissions regulation and anti-tampering provision. OEM can submit OBM results to Granting Type Approval Authority (i.e., the Authority of the Member State that granted the emissions type approval, GTAA) for ISC requirements with the margin below the limit. The manufacturer will be required to perform in-service conformity checks for all ISC families. OBM data could be used for this purpose, enforcing the emissions criteria to select the vehicle/type and supporting the identifications of the conditions in which the test needs to be performed and emissions parameters to be measured. All above are potential benefits able to be applied from the initial OBM phase.

In the long-term (phase 2), OBM aims to replace today's ISC emission testing procedures providing much more qualitative conformity verification since a significantly greater statistical sample is available for evaluation and more reliable conclusions can be extracted.

Table 11-3: Vehicle types/families policies: potential at phase 1 and 2 of OBM implementation

Policy addressed to:	Policy	Phase 1 (short/mid-term): Corresponds to the introduction of EURO 7	Phase 2 (long-term): At a later stage
		Based on improved generations of currently available pollutant sensors	Based on future pollutant sensors
Vehicle types 	ISC emission testing procedures alleviation	• **NOx, NH_3, PM(/PN)**: Reduce emissions testing burden (lower number of measured vehicles)	• **NOx, NH_3, PM/PN**: - Replace emissions testing procedures - Improved qualitative conformity verification: a significantly greater statistical sample can be available • **Other species**: depends on sensor availability
	ISC and MaS vehicle preselection	• Feedback for NOx and NH_3 emissions and DPF diagnostics (via MIL on individual vehicles)	• Feedback for NOx and NH_3, PM/PN and all available species emissions
	Tampering detection	• **NOx:** Cloud-based detection i.e., OBM could detect if many of the same vehicle type are tampered with, which provides indication that the antitampering preventive countermeasures required by the OEMs have not been applied correctly *Note: Preventive security solutions (e.g. secure CAN) are prerequisites for sensor data integrity*	• Cloud-based tampering detection for all pollutants
	Emission compliance and performance monitoring	• **NOx and NH_3**: - Emissions monitoring - Worst-case uncertainties are normalised or can be removed - Emission performance evaluation regardless of boundary and driving conditions • **Other species** emissions monitoring (to be defined)	• **NOx, NH_3, PM/PN and all available species** emissions monitoring (compliance & performance monitoring)

11.4 Testing intelligent vehicles and geofencing functionality

Adaptive control is the generic name of intelligent systems in technology. It may change the performance, behaviour, or control strategy of a vehicle based on external factors or historic data. Hence a simple test on a new vehicle will not bring to light the variations in performance.

Geo-fencing, i.e., zero-emission driving in particular areas is often cited as a pollutant reducing intelligent system. If geo-fencing is reducing emissions in one area, how will it be "compensated" in other areas? Are the overall emissions equal, or even higher, and should that be allowed or desirable? How do you evaluate that (in RDE)? This is general complexity of adaptive control, which also applies to geofencing.

Adaptive automotive control is already a fact. This can make testing complex, as results are no longer simply reproducible and repeatable. (Special settings for testing should no longer be applied.) Cruise Control, Adaptive Cruise Control, Automated Driving, Route information, repeated routes, etc. are all forms of adaptive control. With regenerative systems (DPF, LNT, PHEV) this information is used now. All of these lie outside the scope of current legislation Euro-5/6, which assumes simple deterministic systems and reproducible results of repeated tests.

Technology neutrality is cited often as a principle for proper legislation. However, with Euro-5/6 and Euro-VI technology neutrality is still not achieved, neither in emission limits nor in test protocols. In many cases technology assessments are the basis of European legislation, leading to technology specific legislation. This may hinder innovative solutions and new technologies, which were not included in the original technology assessments, typically many years ahead of legal implementation. Innovative technologies are, almost by definition, not predictable. Appropriate legislation will at least cater for, and preferably stimulate, new and better technologies. Likewise, the very prescriptive testing in Euro-5/6 and Euro-VI, assuming a static technology and control configuration, is already now outdated, as most engines adapt the control for variations in vehicle state and market fuels. If the resulting variations in emissions are below the legal limit, it will have no consequence, but in a strict sense an adaptive emission control is a manipulation device. Therefore, new innovations are hindered by current Euro-5/6 and Euro-VI legislation. Moreover, the example of plug-in hybrid vehicles, and the lengthy development of specific test protocols for these vehicle technologies, shows that specific legislation for specific technologies is a fruitless route towards new vision for mobility, and robust and lasting legislation. The fact that in RDE legislation the treatment of plug-in hybrid electric vehicles differs only in minor details from the conventional vehicles is an example that a different, generic approach to legislation is possible.

New developments in intelligent vehicle technology will make driving more comfortable, safer and simpler. In some cases, intelligent systems may bring environmental benefits, such as geofencing for electric driving mode capable vehicles, disengaging the combustion engine in some areas with special relevance for air quality. Geofencing, i.e., forcing electric driving in geographical areas such as inner cities, is put forward by the car manufacturers as an option to reduce vehicle emission at air-quality hot spots. Such measures are very welcome but must be judged on their effectiveness. If the battery is empty, the vehicle will automatically switch to the combustion engine while driving, despite all intentions. On the other hand, geofencing is one of a whole collection of adaptive vehicle controls which will make vehicles emission performance differ based on the history, location, or time. This can be construed as an Auxiliary Emission-control Strategy, or AES, which will be difficult to describe, as the control parameters may change with time or location. Fundamentally, such adaptive control should do no harm, i.e., should satisfy the same emission requirements as other vehicle usages. Geofencing is intended to do the opposite and lead to a reduction of the emissions and stimulate emission-reducing behaviour.

11.4.1 Initial recommendations

Developments in intelligent vehicle technology lie outside the testing capabilities of current RDE legislation. First, a vehicle may learn to optimise a repeated route, such as with commuting, and it will perform differently after several repeats of the same route. In some cases, like cruise control, driving in parts will be very constant, below normal driving as defined by the RPA boundary. In the case of automated driving, or driving on the basis GPS navigation, systems may be optimised for comfort or fuel consumption, or regeneration moments, showing a different emission performance. In all cases, which cannot be covered naturally in RDE testing, the same “mobility demand” in terms of, for instance, velocity and distance should be compared against similar parts of the RDE test, to ensure that intelligent systems do not have a detrimental effect on the overall vehicle emissions, when active. Therefore, it is essential new testing regime incorporate all normal use and any normal trip. With many prerequisites for testing, as in current RDE testing, the chance that forms of intelligent driving is excluded is large.

If vehicles are self-reporting on the environmental benefits of engaging intelligent systems, like geofencing, such reporting will help to ensure low lifetime emission performance and engaging the car users. However, in these cases such reporting should be validated. This kind of validation is very much in line with the testing for OBM systems. If the vehicles are not self-reporting, the differences between a learned and a default vehicle, and the effect of an engaged system, should be tested for the effect on the emissions. It may not be possible to design an RDE test to cover all different existing, and new forms, of adaptive, learning controls in vehicles. Moreover, within a long test like RDE, the limited operation of, for example, cruise control on the motorway, may not provide a clear and simple comparison to establish the effect of the use of such a system. With any trip as valid emission test, geofencing can be tested and possible effects, such as battery charging while driving before entering a zero-emission zone, included within the testing.

Specifically, geofencing must be combined with appropriate reporting. This reporting should contain the following elements: First, the driver must be informed of the switch to electric drive because of the emission-restricted region. Second, the driver must be aware of which emission-restricted regions are in the vicinity. Third, different control strategies to deal with an empty or low battery charge state in or near an emission-control region must be formalised and described, to allow for different option to deal with such situations. Fourth, the vehicle must store the driving in an emission-control region as evidence for the appropriate control behaviour of the vehicle. Fifth, vehicles must be able to transmit geofencing information to portals associated with the emission-control region and possibly switch to electric driving remotely. GPS data will not be the best and only way to determine an emission-control region in all cases. Portals may help to have robust control.

In principle, if geo-fencing is to be a recognised feature that allow PHEVs to enter, and drive in, a zero-emission zone it should be controllable. First, geofencing functionality should checked during In-Service Conformity testing. Second, geofencing operation must be indicated and recorded in the OBD or OBM so it can be enforced.

Although incomplete, a list of emerging technologies should already provide an idea what future legislation should encompass generically. The new and emerging technologies require different types of emission testing includes: Geofencing (e.g., zero-emission driving only in specific regions), adaptive cruise control, active safety systems, and automated driving, far ahead looking engine and emission control from, e.g., satellite navigation over a full trip, and fixed routes, and future technologies based on connected cars, mobility-as-a-service, etc. Their operation may often lie outside current RDE boundaries because of route and vehicle use. Moreover, adaptive, learning control will also interfere with AES declarations: the same vehicle model may perform differently on the same RDE test, based on the differences in (learning and use) history of the vehicle. Moreover, a failure to comply with the zero-emission requirements, for example, by driving with an empty battery should lead to inducements to charge like limp modes, as exists for empty AdBlue tanks, and eventually, blocking the engine start. These kinds of requirements must be augmented with appropriate information for the vehicle user that is related to trips that include geofencing zones and the range available.

The electric driving range of a PHEV will be limited if the vehicle is not charged. Moreover, if a PHEV is driving only short trips without off-vehicle charging in between it may not even charge the battery to the extent that the cold start can be reduced. Some vehicles are used in this manner, for example, only for local shopping trips. It is important to incorporate this kind of vehicles use over longer periods in the tests' procedures. With adaptive control the vehicle use over a longer period will be more important, as vehicles can adapt to ensure low emissions in these cases, when it is incorporated in the design.

12 Summary of the recommendations

This section provides a summary of the final recommendations for EURO 7 regarding recommended pollutants for regulation and their respective recommended emission limits based on the analysis and evidence presented in the preceding chapters. Limits are recommended for tailpipe emissions of all on-road vehicles and for evaporative emissions of cars and vans. While technological capabilities regarding the reduction of emissions from brake and tyre wear were examined, specific limits are not recommended as part of this study.

12.1 Tailpipe emissions

This section outlines the recommended pollutants for regulation under EURO 7. These pollutants and whether they are recommended to be measured on-road or in-laboratory are summarised in Table 12-1: below.

Table 12-1: Recommended pollutants for regulation and their measurement under EURO 7. Testing procedures are described in Chapter 6 of this report

	NOx	CO	SPN_{10}	PM	NH_3	N_2O	CH_4	HCHO	NMOG	THC
Measured or not	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Calc. (2)	Yes
LIMIT on-road	Yes	Yes	Yes	No (3)	Yes	Yes (1)	Yes (1)	Yes	No (3)	No (3)
LIMIT in-lab	No (4)	No (4)	No (4)	Yes	No (4)	Yes (1)	Yes (1)	No (4)	Yes	No (4)

(1) Option a. To limit N_2O and CH_4 individually. Option b. To limit sum of N_2O and CH_4 emissions.
(2) THC, HCHO, CH_4 need to be measured as a minimum for calculation of NMOG, but other emissions may be needed (see list of four options in Chapter 3.4).
(3) If PEMS is sufficiently accurate and vehicle installation is practical, NMOG, THC and PM can be measured on-road subject to the same limits as in-lab.
(4) On-road limits apply, if measured in-laboratory on chassis or engine dynamometer.

Based on the evaluation, the recommended new gaseous pollutants to be covered are NH_3, N_2O, CH_4, NMOG and formaldehyde:

- ***NH_3*** potentially induced by exhaust emission control devices (e.g., SCR and TWC) is recommended to be limited individually.
- ***CH_4*** and ***N_2O*** are recommended to be controlled and their levels accurately determined, but two options are identified for limiting these emission species: a) limiting CH_4 and N_2O emissions separately b) limiting the sum of CH_4 and N_2O, expressed as a total cap.
- ***HCHO*** is harmful at very low concentrations, and potentially emitted from alcohol and diesel engines, hence it is recommended to be limited individually.
- Extending THC to ***NMOG*** emissions is recommended to consider aldehyde and alcohol emissions originating from oxygenated fuels.

- ***NO_2*** is not recommended to be limited individually, instead a NOx limit is recommended as being sufficiently low to also limit NO_2.

Vehicular particle mass and number emissions are also recommended to be covered in EURO 7. It is recommended that filter-based PM is retained, to ensure that volatile materials excluded by solid particle methods are quantified and limited. It is recommended that the current regulatory SPN_{23} metric will be replaced by a similar method with a lower size threshold in the range of 7-10 nm (***SPN_{10}***) in order to ensure that metal oxides and other <23nm particle emissions are quantified and limited. Future legislative activities should recommend the fitment of efficient particle filters to all ICE to reduce non-volatile particles of all chemistries.

12.1.1 LDV

CLOVE proposes the introduction of a two-area form of limit. Under this two-area form of limit, a constant limit value in mg (or particles for PN emissions), referred to as a “budget”, is applied up to a reference distance of 16 km (a reference distance of 10 km is also briefly discussed in this report as an alternative), while a constant limit in mg/km (or p/km for PN emissions) is applied for trips above 16 km. The budget must be calculated from the mg/km value applied to the same pollutant. The rationale behind the selection of 16 km reference distance and the exact limit values for the budget and constant (per km) limits are further explained in in Section 7.4 of this report. An illustrative example of this two-area limit form is presented in Figure 12-1 below. It needs to be stressed that the distance up to 2 km is recommended to be associated with a driving power restriction that is applied in normal conditions of use up to this distance within the “budget” zone.

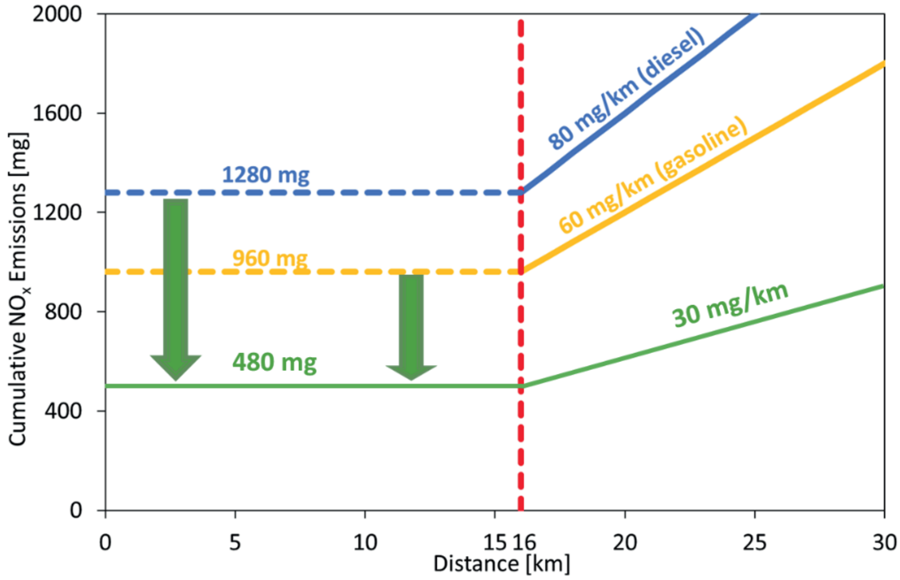


Figure 12-1: Recommended functional form of EURO 7 limits (example of NOx, scenario 1, normal conditions) in comparison to current Euro 6 approach (without conformity factor)

The recommended limits for cars and vans under EURO 7 are presented in Table 12-2: below.

Table 12-2: Recommended emission limits in mg/km for cars and vans under normal conditions for Scenarios 1 and 2. The budget is calculated from the mg/km value multiplied by 16 km.

Pollutant	CO	NMOG	NOx	PM	PN_{10}	NH_3	CH_4	N_2O	HCHO
Unit	mg/km	mg/km	mg/km	mg/km	#/km	mg/km	mg/km	mg/km	mg/km
Scenario 1									
Cars and Vans	400	45	30	2	1×10^{11}	10	20	20	5
Vans with TPMLM>2500 kg & PWR<35 kW/t	600	45	45	2	1×10^{11}	10	20	30	10
Scenario 2									
Cars and Vans	400	25	20	2	1×10^{11}	10	10	10	5
Vans with TPMLM>2500 kg & PWR<35 kW/t	600	25	30	2	1×10^{11}	10	10	15	10

The limits presented apply to those trips that fall within the recommended testing and evaluation boundaries for "normal" driving conditions, as defined in Table 12-3 below. As shown in Table 12-2, the recommended emission limits for LCVs (with TPMLM>2500 kg & PWR<35 kW/t) for CO, NOx, and N_2O are 50% higher compared to the respective limits of passenger cars (HCHO limits are two times higher). This multiplier of ×1.5 is derived from the ratio of current Euro 6 limits in N1-Class III compared to M1 and takes into account the expected improvement in EURO 7 technologies. No extra allowance is applied in the case of NMOG, NH_3, CH_4, PM and PN emissions, as it is expected that EURO 7 technologies will be able to control emission levels of these species.

Table 12-3: Recommended testing and evaluation boundaries for normal and extended conditions

	Normal	Extended
Distance based budget	16 km	16 km
Trip and driving	Any	Any
Ambient temperature	-7°C to 35°C	-10°C to 45°C
Altitude	1 600 m	2 200 m
Minimum mileage	3 000 km	Any
Maximum velocity	<160 km/h	speed limit

	Normal	Extended
Towing/roofbox/etc.	None	Included
Cold start power restriction	up to 2 km	None

Table 12-4: Recommended durability requirements for normal and extended conditions

Parameter	Normal	Extended
Maximum age or mileage	240 000 km/15 years	240 000 km/15 years

An emission limit multiplier of ×3 is recommended to be applied in emission limits during "extended conditions" of use (see Table 12-3). The circumstances under which this multiplier is applied are summarised as follows:

- The x3 multiplier is recommended to be applied even if one condition falls within the extended conditions.
- If more than one condition falls within extended conditions (e.g., low temperature and trailer and high altitude), the ×3 multiplier is recommended to be applied only once.
- The recommended applications of the ×3 multiplier are:
    - within budget distance (16 km): if any condition falls within extended conditions once, the ×3 factor is applied to the whole budget.
    - beyond 16 km: the ×3 factor is applied only during the extended conditions period, not for the complete test. The exact implementation method/approach is to be defined.

Regarding durability requirements, the recommended limit values correspond to 160 000 km and 8 years. Further deterioration factors will need to be applied up to 240 000 km. These factors will be determined by an on-going parallel project.

12.1.2 HDV

Based on the evaluation results outlined in chapter 8, the recommended testing conditions for EURO 7 HDVs are presented in Table 12-5 below. These are based on a similar concept to that described for LDVs, accounting for the unique features of HDVs.

Table 12-5: Recommended testing conditions for EURO 7 HDVs

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Ambient temperature	-7°C to 35°C	-7°C to 35°C	-10°C to +45 C [a]
Cold start	Evaluation from $t_{coolant}$ > 30°C on; cold start weighted with 14%	Test evaluation from engine start on; extra limits for cold start	Test evaluation from engine start on; extra limits for cold start

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Auxiliaries use	None	Possible as per normal use	Possible as per normal use
Min Trip duration	> 4 x WHTC work	Any [b]	Any [b]
Evaluation	1 WHTC window	Ref. work, ref power method [c]	"Extension Factor [d]"
Engine load [kW/kW_{rated}]	Only work windows > 10% valid	Any [e]	Any [e]
Payload	10-100 %	0%-100% [f]	0%-100% [f]
Max. altitude [m]	1 600 m	1 600 m	2 200m
Trip composition	Depending on class of vehicle	Normal trip as intended usage	Normal trip as intended usage
Minimum km before testing	15 000 km (>60 hours)	3 000 km for <16t TPMLM 6 000 km for >16t TPMLM	All > 300 km

[a]: Extra provision for maximum AdBlue defrosting time suggested for lower temperatures
[b]: In combination with the "Budget" Limit approach described in chapter 5, no minimum test time is required.
[c]: The details of the recommended evaluation method is described in chapter 8.
[f]: Values show allowed range, the minimum payload results from weight of driver and test equipment
[d]: For a simple regulation, for the time driven in the extended conditions range, the measured emissions shall be divided by 2, independently of how many of the parameters are in the extended range. The "time" refers to 1 Hz recorded signals after time alignment of emissions and corresponding test conditions.
[e]: With reference power method
[f]: Values show allowed range, the minimum payload results from weight of driver and test equipment.

Table 12-6: Recommended useful life for EURO 7 HDVs

Parameter	Current ISC	EURO 7 Normal conditions	EURO 7 Extended conditions
Durability [km]	N2, N3<16t, M3: 300k km N3 > 16t: 700k km	N2, N3<16t, M3: 700k km N3 > 16t: 1 200k km	N2, N3<16t, M3: 700k km N3 > 16t: 1 200k km

Note: The durability of the emission control systems until the end of their lifetime will be dealt with separately

Different limits for hot and for cold driving conditions are recommended for EURO 7. The corresponding limit regime is designed as follows:

- The cold phase and the beginning of hot conditions are limited by a "budget", which defines the maximum emissions allowed for a test, up to an engine work of 3 x WHTC. This budget is defined by a corresponding limit $[mg/kWh]_{Budget}$ and the kWh work the tested engine delivers in 3 x WHTC. Any test up to 3 x WHTC work must be below the resulting limit in [mg/test].
- The hot emissions are limited by a separate $[mg/kWh]_{hot}$ limit, which has to be met under hot conditions.
- To safeguard the MAWs not covered by the possible 90th percentile approach, a "100th percentile" limit is added, which must not be exceeded in any MAW between the first and last second of a test.

Overall, the base limit scheme leads to a set of 3 limit values for HDVs, which are also illustrated in Figure 12-2:

1. "Budget" for all tests below 3 x WHTC work
2. "100th Percentile" for all MAWs between 1st and last second of the test
3. "90th Percentile" for all MAWs beginning 10 minutes after the engine was started in the test.

The hot emissions are limited by a 90th percentile of MAWs and the 100th percentile limit is applicable over the entire test not only limiting the cold start phase (e.g., for NH3 highest emissions are expected under hot and high load conditions).

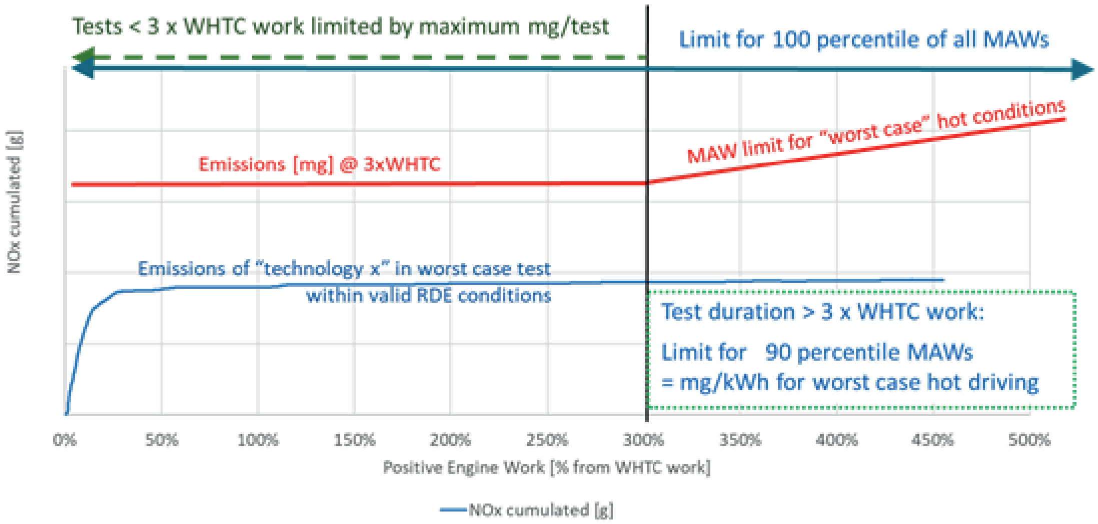


Figure 12-2: Scheme of the possible emission limit regime for EURO 7 HDV RDE testing

The limits achievable by the single engine concepts and technologies have been compiled into a fuel neutral set of limits and are presented in Table 12-7. These illustrate the levels achievable by these technologies and form the recommendation for combined limits for HDVs. The different limits for the different technology do not mean that we suggest different emission limits to be implemented in EURO 7.

Table 12-7: Limits for the two EURO 7 technology packages (H2 and H3) assuming the EURO VI durability requirements in mg/kWh (#/kWh for PN)

100th Percentile Limits**	NOx	SPN_{10}	PM	CO	NMOG[c]	NH_3	N_2O*	CH_4*
H2[a] (EURO 7 w/o pre-heating)	350	5×10^{11}	12	7500	200	70	300	500
H3[b] (EURO 7+pre-heating)	175	5×10^{11}	12	3000	75	70	300	500
90th Percentile Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG[c]**	**NH_3**	**N_2O***	**CH_4***
H2[a] (EURO 7 w/o pre-heating)	90	1×10^{11}	8	300	50	70	60	350
H3[b] (EURO 7+pre-heating)	90	1×10^{11}	8	300	50	70	60	350
Budget Limits	**NOx**	**SPN_{10}**	**PM**	**CO**	**NMOG[c]**	**NH_3**	**N_2O**	**CH_4**

H2[a] (EURO 7 w/o pre-heating)	150	2×10^{11}	10	2700	75	70	260	500
H3[b] (EURO 7+preheating)	100	2×10^{11}	10	1200	50	70	260	500

* Limit composition for CH_4 and N_2O results in less than 5% share of CO_2e emissions vs. tailpipe CO_2 in worst-case conditions (average will be lower). Limits applicable to cycle averages, not suggested for each MAW.

** For HCHO a limit value of 30 mg/kWh is assumed to be feasible for the H1 and H2 technologies and is in line with the PEMS analyser capabilities. The value should be validated later, since HCHO was not measured in the EURO 7 demonstrator tests and simulation of HCHO was not possible for HDVs.

a: HDV with optimised engines and close-coupled emission control systems combined with underfloor systems.

b: As H2 but with pre-heating of the close-coupled emission control system before engine starts.

c: For HCHO a limit value of 30 mg/kWh is assumed to be feasible for the H1 and H2 technologies and is in line with the PEMS analyser capabilities. The value should be validated later, since HCHO was not measured in the EURO 7 demonstrator tests and simulation of HCHO was not possible for HDVs.

Long idling emission tests can be covered by the budget-limit values expressed in the table above and may be examined also as isolated idling test.

Shorter idling phases do not require specific provisions, as long as the reference power method is applied in all test areas (budget, hot and 100th percentile limit) and the share of idling is not excessively long. For short tests, this involves applying the “Reference Power” method together with the “Budget” limits for short tests (<3xWHTC work) as outlined in equation 8-8, whereby the power is simply set to 10% of the rated power and multiplied with the budget limit value (see Table 12-7).

Equation 8-8	$\text{Limit [g/h]} = \text{Limit}_{\text{Budget}} \text{[g/kWh]} * P_{\text{rated}} * 0.1$

Using equation 8-8 for example for the limit values elaborated for HD 2 in the table above, which has a 330 kW rated power HD engine, leads to the idling limits outlined in Table 12-8.

Table 12-8: Example for idling emission limits resulting from the recommended approach and the limit values from Table 8-9 for the HD 2 technology with a 330 kW rated power HD engine in [g/h]

g/h	NOx	SPN_{10}	PM	CO	NMOG	NH_3	N_2O	CH_4
HD 2	4.95	6.6×10^{12}	0.33	41	2.48	2.15	4.6	1.0

12.2 Evaporative emissions

It is recommended that limits for evaporative emissions account for vehicle size, with one limit applicable to passenger cars and small light commercial vehicles (<2.5t TPMLM) and a higher limit for heavier light commercial vehicles (>2.5t TPMLM). These limits are outlined in Table 12-9 below.

Table 12-9: Recommended evaporative emission limits

	PCs and LCVs < 2.5t TPMLM (N1 class I-II)	LCVs > 2.5t TPMLM (N1 class III)
Diurnal and hot soak emissions limit	0.50 g/day (48 h test, worst of 2 days)	0.70 g/day (48 h test, worst of 2 days)

	0.30 g/day (48 h test, worst of 2 days)	0.50 g/day (48 h test, worst of 2 days)
Refuelling emissions (ORVR)	0.05 g/L	
Leak threshold	0.5 mm (~0.02 inch) diameter	

A reduced emission limit (expressed in grams per day) is recommended for the SHED test. The duration of the diurnal test is recommended to remain as it is currently (48 hours), whereby an emissions result is determined for each of the two days of the SHED test and the highest (including hot soak) is compared to the limit. A higher temperature of 38°C is recommended for the hot soak test. To ensure sufficient purging prior to the SHED test, the soak and drive temperature is not prescribed, but can range from 25 to 38°C. Further testing conditions are outlined in Chapter 9 of this report.

A limit for refuelling emissions of 0.05 g/L is also recommended. For running losses, no dedicated limit is deemed necessary if the suggested limits on diurnal and refuelling emissions are adopted.

Furthermore, an OBD leakage detection requirement of 0.5 mm (~0.02 inch) for the minimum leak diameter to be detected is also recommended.

12.3 Non-exhaust PM emissions

Non-exhaust PM abrasion emissions heavily contribute to total PM emissions from road transport. In 2017, it was assessed that total non-exhaust PM_{10} emissions were of the same level as exhaust ones with the former exhibiting an increasing trend compared to the decreasing trend of the latter.

Emissions from brakes in particular are considered toxic due to the high content of transitional metals contained in brake pads and discs. Therefore, brake emissions control can be considered a priority as it remains largely unknown how electrified technologies will affect brake PM emissions. Electric powertrains may benefit from decreased mechanical brake use to the benefit of brake energy recuperation, but they are also heavier than conventional powertrains which means higher braking forces are required.

Several technologies exist to control emissions from brakes already today. These range from improved pads, particle collection methods, coated discs, enclosed brake encapsulation and enhanced energy recuperation for vehicles equipped with internal combustion engines (hybrid or conventional). However, relevant research has only focused on light-duty vehicles. Heavy-duty brake emissions testing and characterisation is less prevalent.

Emissions from tyres and road wear abrasion are more difficult to characterise as they depend a lot on road surface quality and condition as well as environmental conditions. Before considering their control, one will have to develop more specific characterisation protocols and better understand tyre/road interactions.

Based on examination of the current literature and the data of the CLOVE consortium, the current average level of PM_{10} brake emissions from passenger cars is estimated at 11 mg/km assuming low steel brake pads use and 15% regenerative braking penetration in the fleet. This value comes from several studies, often using different sampling protocols. When a sampling protocol, currently being discussed at PMP has been defined, the average emission level may need to be varied to reflect those protocol conditions.

Any future values for emission limits that can be proposed come also with the limitation of an unavailable defined sampling protocol. With today's knowledge though a mild reduction of emission limit may be set at 7 mg/km, assuming non-asbestos pads and an increased presence of regenerative braking. A second, more stringent limit, may be set at 5 mg/km assuming non-asbestos pads, increased regenerative braking and particle collection methods at least in some of the heavier vehicles.

It is recommended that these values are proportionally adjusted for heavier LCVs.

12.4 On-Board Monitoring

The introduction of an OBM system is recommended to resolve OBD system's shortcomings and provide lifetime emission compliance of future vehicles. The OBM system is recommended to track emission-related data for each vehicle using tailpipe sensors and simulation models. Via the on-board control units (i.e., engine and communication control units), these data can be available for either on-board or on-the-cloud data processing. Due to the limited availability and capabilities of exhaust sensors, a 2-phase approach is necessary. For the short term (phase 1), NOx, NH_3 and PM/PN emissions can be monitored based on an improved generation of currently available sensors and diagnostic algorithms. A further evaluation is necessary for the model-based monitoring of CO/HC/CH_4 emissions. In the long term (phase 2), on-board monitoring will only become technically feasible for all pollutants with significantly improved and newly developed sensors. The technical capabilities and the specific challenges that should be addressed for both phases are outlined in Table 12-10.

Table 12-10: Short/mid-term and long-term capabilities of tailpipe sensors for OBM

Short/mid-term capabilities (phase 1)	Long-term capabilities
• **NOx:** Amperometric next generation sensors - "Dew-point" free + Water resistance • **NH_3** (diesel): Mixed-potential next gen. sensor (available in the market but further assessment is needed). Utilisation of NOx sensor via separation algorithms or a composite NOx+ NH_3 monitoring are currently investigated • **NH_3** (petrol): Utilise cross sensitivity of NOx sensor (λ<1) • **PM(/PN)** (diesel): Based on advanced filter diagnostics → resistive next generation sensors • **(PM/)PN** (petrol): Based on advanced filter diagnostics → pressure or temperature or OSC-based	• **NOx, NH_3**: Improved NOx and NH_3 sensors: - Accuracy: <±7 ppm or <± 7 % - "Dew-point" free + Water resistance improvements for all sensors - Reduced NH_3 cross-sensitivity - Separate Engine-out and tailpipe sensors • **PM/PN:** Advanced sensor technologies (Resistive, Electrostatic, Diffusion Charge, Laser Induced Incandescence) • **CO/HC/CH_4, other species:** currently not developed but feasible with appropriate lead time

Short/mid-term capabilities (phase 1)	Long-term capabilities
• **$CO/HC/CH_4$:** Partially with model-based monitoring (further evaluation is needed)	

The higher uncertainty of the on-board sensors and models compared to PEMS or laboratory measurement systems (expressed as OBM tolerance) should be considered for the proposed OBM policies. These are estimated in the order of ±100-200% of the relative EURO 7 emission limits: an OBM system with optimised next-generation NOx amperometric sensors can achieve a ±100% (or lower) tolerance while NH_3 monitoring or any model-based monitoring (e.g., for CO) will require higher tolerances (>200%).

Finally, specific OBM policies are recommended (Table 12-11). These policies are addressed either to individual vehicles (relevant for future possible introduction in the Roadworthiness context) or to vehicle types (relevant for type approval framework, for ISC or MaS compliance checking).

Table 12-11: Recommended policies for OBM

Addressed to:	Policies
Individual vehicle	Identification of high-emitters and enforcement to repair
	Tampering detection
	Improved roadworthiness inspections
	Long-term evaluation of emission performance
Vehicle types	ISC emission testing procedures alleviation
	Tampering detection
	ISC and MaS vehicle preselection
	Emission compliance and performance monitoring

Abbreviations and Acronyms

AECC	Association for Emissions Control by Catalyst
AFR	Air fuel ratio
AGVES	Advisory Group on Vehicle Future Emission Standards
AP	Air pollutant
AQ	Air quality
ASC	Ammonia slip catalyst
BAB130	Bundesautobahn (German for federal highway) test cycle
BAT	Best available technology
BC	Black carbon
BEV	Battery electric vehicle
CAN	Controller Area Network
CAV	Connected autonomous vehicle
CBA	Cost benefit analysis
cc	Close-coupled
CEN	European Committee for Standardization (CEN, French: Comité Européen de Normalisation)
CF	Conformity factor
CNG	Compressed Natural Gas
CoC	Certificate of conformity
CO_2e	CO_2 equivalent emissions with the GWPs for N_2O=265 and CH_4 = 28
CPC	Condensation particle counter
CUC	Clean Up Catalyst
D	Deliverable of project
DAD	Diode array detector
DC	Diffusion Charger
DNPH/HPLC	2,4-dinitrophenylhydrazine/high-performance liquid chromatography
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EATS	Exhaust emission control system

EC	European Commission
EEA	European Environment Agency
EFM	Exhaust Flow Meter
EGR	Exhaust gas recirculation
EHC or E-cat	Electrically heated catalyst
EM	Electric machine
EMF	Electromotive force
EPA	United States Environmental Protection Agency
EU	European Union
E-cat	*See EHC*
FE	Filtration efficiency
FEM	Finite element model
FET	Field-effect transistor-based sensors
FFDS	Full flow dilution systems
FID	Flame ionisation detector
FPI	Fabry-Perot Interferometer
FTIR	Fourier Transform Infrared Spectroscopy
FTP	Federal Test Procedure
GC	Gas chromatograph
GDI	Petrol direct injection
GHG	Greenhouse Gas(es)
(c)GPF	(coated) Petrol particulate filter
GWP	Global Warming Potential (100 year GWPs from 5th IPCC assessment are used)
HCB	hexachlorobenzene
HCI	Hydro-Carbon Injection
HCT	Hydrocarbon trap
HDV	Heavy duty vehicle
HEV	Hybrid electric vehicle
HP	High pressure
HPDI	High pressure direct injection

HPLC	High performance liquid chromatographer
HV	High voltage
IARC	International Agency for Research on Cancer
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
ISC	In service conformity
IUPR	In-Use Performance Ratios
LCV	Light commercial vehicle
LDV	Light duty vehicle
LEV	Low-emission vehicle
LII	Laser-Induced Incandescence sensor
LNG	Liquified Natural Gas
LNT	Lean NOx Trap
LOD	Limit of detection
LOQ	Limit of quantification
LP	Low pressure
/M	Month of project
MCA	Multi Criteria Analysis
MaS	Market surveillance
Mas	Market Surveillance
MAW	Moving Average Window
MEMS	Micro-electro-mechanical systems
MiL	Malfunction indicator lamp
MIR	Maximum Incremental Reactivity
MS	Member State
NDIR	Non-dispersive infrared
NDUV	Non-dispersive ultraviolet
NECD	National Emissions Ceiling Directive
NEDC	New European Driving Cycle
NGO	Non-governmental organisations

NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NMVOC	Non-methane volatile organic compound
NSC	NOx storage catalyst
NTE	Non-to-exceed
OBD	On board diagnostics
OBFCM	On board fuel consumption monitoring
OBM	On board measurement
OEM	Original equipment manufacturer
OPF	Otto particulate filter
OSC	Oxygen storage capacity
OTA	Over the Air
OTL	On-Board Threshold emission Limit
PAHs	Polycyclic aromatic hydrocarbon
PASS	Photo-acoustic soot sensor
PC	Passenger car
PCBs	Polychlorinated biphenyls
PEMS	Portable emission measurement system
PFDS	Partial flow dilution system
PGM	Platinum group metals
PHEV	Plug-in hybrid electric vehicle
PMP	Particle measurement programme
POPs	Persistent organic pollutants
pSCR	Passive SCR
PTI	Periodic Technical Inspection
PTR	Proton Transfer Reaction
QCL	Quantum Cascade Laser Analyser
RDE	Real drive emissions
REAL	Real emissions assessment logging
RPA	Relative Positive Acceleration

RS	Remote sensing
RSI	Road-side Inspection
SCR	Selective catalytic reduction
SCRF/SDPF	SCR-coated DPF
SEMS	Sensor/Smart emission measurement system
SVC	Semi-volatile compounds
TA	Type approval
TaL	Time above limit
TEFs	Toxic equivalency factors
TfL	Transport for London
THC	Total hydrocarbons
ToR	Terms of Reference
TPN	Total Particle Number
TRL	Technology readiness level
TWC	Three-way catalyst
uf	Under-floor
$v*a_{pos}$ [95]	95th percentile of positive products of vehicle velocity and acceleration
VPR	Volatile particle remover
VTP	Verification testing procedure
WHO	World Health Organisation
WHSC	World Harmonised Steady State Cycle
WHTC	World Harmonised Transient Cycle
WHVC	World Harmonised Vehicle Cycle
WLTP	Worldwide harmonised Light Vehicle Procedure
W_{pos-R}	Reference Work
ZEV	Zero-emission vehicle
3WC	Three way catalyst
4WC	Four way catalyst (TWC+GPF)

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