Green NCAP, Evaluation of the Exhaust Gas Behaviour and the Energy Efficiency of Modern Cars under Demanding Conditions

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Contents

Summary

In 2019, Euro NCAP launched Green NCAP, a new initiative to evaluate the environmental behaviour of new cars that is complementary to its consumer safety programme. The vehicles are rated based on performance indices – Clean Air, Energy Efficiency and Greenhouse Gases. The tested models range from conventional powertrains to battery electric cars as well as the latest fuel cell technology. The tests cover a wide range of challenging conditions, far beyond the requirements of type-approval, both in the lab and on the street. Apart from the typical pollutants considered by EU law, the not yet regulated compounds N_2O and NH_3 are already measured and investigations are ongoing to include emissions of sub-23nm particles. The initial results confirm the significant improvement in exhaust gas quality achieved over the last years but also identify necessities for further development. Several paradigm changes are and will be introduced in future programme activities.

1 Introduction and Problem Statement

Consumers today operate in increasingly complex markets, challenged by growing amounts of information and an increasing choice of products. This is particularly true for the process of buying a “green” vehicle. A vehicle is one of the most expensive purchases made by individuals or households, often equal to many months or even years of income and it will last for many years. But whereas sustainability and environmental impact are increasingly important considerations, many consumers lack the insights and knowledge and are confused by the information in the media to make sound choices when it comes to purchasing the most environmentally friendly vehicle available within their budget.

The Green New Car Assessment Programme, or Green NCAP [1], wants to provide a reference for consumers' choice and purchase for clean vehicles, by revealing the true environmental performance of new cars in objective and meaningful tests. The consumer information programme is modelled after the successful European vehicle safety programme that runs under the name Euro NCAP [2]. The strong consumer-oriented basis allows Green NCAP to reach out directly to over 180 million consumers world-wide via members' communication channels and those of the organisation itself.

As an advocate for clean and energy efficient vehicles, Green NCAP aims to highlight failings and weaknesses of pollutant abatement as well as greenhouse gas emission control. For the consumer and fleet operator, fuel/energy consumption and driving range are also important considerations when purchasing eco-friendly cars. Green NCAP challenges vehicle manufacturers on the products they are selling by informing the market in a transparent, objective yet simple manner about the environmental performance of new cars. The latest state-of-the art measurement techniques and associated equipment are used, pushing for innovation, research and development of technology. The Green NCAP programme aims to spark competition between manufacturers and targets an upward spiral of the environmental performance of vehicles at lowest cost for the environment, society and the individual consumer.

Type-approval framework Regulation (EU) 2018/858 [3], supplemented by Euro 6 Regulation (EC) No 715/2007 [4] and its implementing Regulation (EU) 2017/1151 [5], UN Regulations No. 83 [6] and No. 101 [7] largely set-out the environmental performance requirements that new vehicle types need to comply with before being placed on the market today. Approval legislation concerns vehicle types and families but boils down to requirements for individual vehicles. CO_2 fleet emission requirements, laid down in Regulation (EU) 2019/631 [8], also need to be complied with by the industry. This leads to balancing zero-tailpipe emission vehicles introduced on the market against higher tailpipe emitting CO_2 vehicles, to avoid high penalties collected by the authorities in case of non-compliance. This mechanism is also exerting pressure on the industry to introduce vehicles with improved fuel/energy efficiency. At the same time this policy seems to lead to small fuel-efficient cars to disappear from the market as manufacturers do not deem it commercially viable to equip these with electrified propulsions or advanced engine technologies. Another adverse effect of the EU policy is the continuous increase of the average vehicle mass, which is a highly critical design parameter for the overall energy efficiency of a car.

Looking forward, significant changes are anticipated to the regulatory landscape and to the content of environmental performance requirements. The European Commission is developing Euro 7 targeting application for new vehicle types to comply with as of 2025. The Commission also revised Regulation (EU) 2019/631 [8] in July 2021 to help achieve a climate-neutral EU by 2050. To meet the intermediate 2030 target of at least 55 % net reduction in greenhouse gas emission reduction compared to 1990 for all sectors, the Commission prepared a revision of the Regulation as part of the 'Fit for 55 %' package. Green NCAP is determined to remain ahead of these latest legislative requirements, both at the EU and UNECE levels.

Typically, legislation includes harmonised, specific test requirements and performance criteria in its scope against which shall be tested to determine whether a vehicle type complies or does not comply with the applicable requirements. A vehicle type either passes or fails the legislative tests. There is little additional benefit to the vehicle manufacturer to design and market vehicles that are significantly cleaner or more fuel efficient. Measured greenhouse gas emissions are limited to CO_2 only, which are regulated for the total vehicle fleet that a vehicle manufacturer makes available on the market, rather than for the individual vehicle type, variant and version. This allows for significant differences between cars, even within brands and model range.

Manufacturers tend to deal separately with type-approval requirements and the legal requirements laid down for CO_2 emissions by the fleet on the EU market. Green NCAP has set out requirements for the individual vehicle that is tested and rated. It needed to break new grounds, setting upper and lower performance thresholds for each relevant emission constituent. A fair but strict scoring and rating scheme has been developed and is continuously being improved and upgraded. This allows for stakeholders to differentiate between green and less green vehicles, for consumers through a simple 0 - 5 stars rating scheme. For experts, a high level of data granularity and detail can be made available upon request and if needed. Despite a higher level of ambition compared to legislation and continuously pushing the industry to fit state-of-the-art emission abatement and fuel/energy saving technology on every vehicle, also on low-end bread ‘n butter cars, it is very important that cars remain affordable.

The test results presented in this article are gained in the course of the pilot project “Green Vehicle Index” (GVI), which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 814794 [9].

2 Methodology

The vehicle’s environmental behaviour is generally composed of three main design constraints that have to be carefully balanced with trade-offs in each area that may adversely affect each other: control of pollutant emissions, control of energy efficiency and control over propulsion unit performance. To adequately address these aspects, a detailed testing methodology with focus on environmental performance and robustness was carefully developed. The obtained results are transferred by the rating methodology into rating scores and number of stars that can be easily understood by consumers.

2.1 Testing Methodology

In general, WLTP and RDE sample points only partly cover the engine map. Green NCAP aims to also take non-evaluated points under the maximum power curve into account, ensuring that the vehicle is robust in its entire engine map, Fig. 1. Furthermore, Green NCAP tests cover a wider range of ambient conditions. This is the reason why laboratory testing is carried out at 14 ºC of ambient temperature, which is a more representative temperature around Europe than the default 23 ºC. In addition, engine cold start and warming-up testing at -7 ºC ambient temperature are included. Tests are conducted both on the chassis dynamometer and on the road, Tab. 1 and Tab. 2.

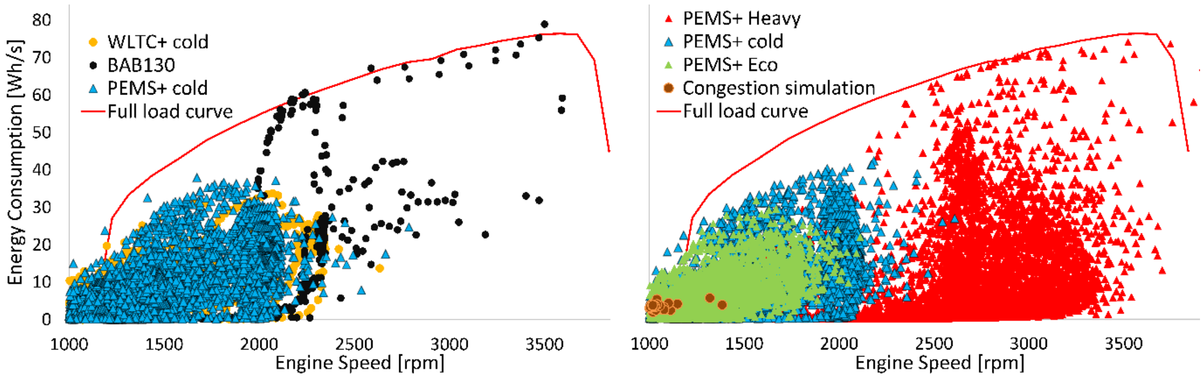

Fig. 1 Energy consumption over the engine speed at different tests and full load operation curve. Measurement sampling of a 110 kW Euro 6d-temp diesel vehicle.

Tab. 1 Chassis dynamometer tests in the Green NCAP test programme.

Test name	WLTC+ Cold	WLTC+ CAT	BAB130	WLTC+ Warm
Type	Chassis dynamometer			
Ambient temp. and soaking	14°C	-7°C	14°C	14°C
Start	Cold	Cold	Warm	Warm
Auxiliaries	Air-conditioning set at 23°C, daytime running lights on, radio on			
Gear shifting	GSI (According to Regulation (EU) No 65/2012 [10])	GSI (According to Regulation (EU) No 65/2012 [10]	4^{th}: 80-130 6^{th}: 110-130 Or: kick-down	GSI (According to Regulation (EU) No 65/2012 [10]
Constituents	CO_2, CO, NO_x, NO, NO_2, PN23, THC, CH_4, PM, NH_3, N_2O			
Purpose	Check comparability to CoC; conducted twice to check repeatability and PEMS correlation.	Challenge the aftertreatment systems (and/or electric vehicle systems) with sub-zero ambient temperatures	Fully depressed pedal accelerations, high-end and maximum engine load conditions	Determine the influence of the cold start at WLTC+ Cold; checks for unusual aftertreatment application

Besides the standard gaseous and particle emissions, the not yet regulated species N_2O (nitrous oxide) and NH_3 (ammonia) as well as CH_4 (Methane, which is not regulated as a GHG), are measured and evaluated in the chassis dyno tests. Parallel research activities with focus on sub-23nm particles were carried out both in the lab and on the road.

As a part of the real-world testing, a **congestion simulation** is performed. The purpose is to check whether the exhaust emissions can be controlled properly when the engine is idling frequently, which might often occur in urban areas.
In order to assess the vehicles behaviour during **short urban trips** with cold engine start, the first 8 kilometres of the two PEMS+ Cold tests are evaluated separately.

Tab. 2 On-road driving tests (PEMS+) in the Green NCAP test programme.

Test name	PEMS+ Cold	PEMS+ Eco	PEMS+ Heavy
Type	On-road (real-world testing)		
Trip requirements	As type-approval		
Ambient boundaries			
Soaking conditions	23 +/- 3 °C	-	-
Start	Cold	Warm	Warm
Driving dynamics	As type-approval	Smooth driving, moderate braking	Dynamic driving, aggressive braking
Payload	Fixed at 70 %	Min. payload	Fixed at 90 %
Auxiliaries	A/C at 23 °C, lights on, radio on	A/C off, lights at auto, radio on	A/C, lights, radio on, seat and rear window heating
Gear shifting	GSI (According to Regulation (EU) No 65/2012 [10])	GSI (According to Regulation (EU) No 65/2012 [10])	Aggressive
Start-stop system	on	on	off
Motorway speed	110-120 km/h	100 km/h	120-130 km/h
Idling and accelerations	N/A	15 min of idling in urban part (engine on)	15 min of idling before test, 9 full load accelerations
Constituents	CO_2, CO, NO_x, NO, NO_2, PN23		
Purpose	Standard conditions; comparability to type-approval; conducted twice	Fuel saving, Eco-friendly, driving; challenge low temperature behaviour of aftertreatment and robustness in low power demand operation	Sporty, dynamic, aggressive driving with heavy load; challenge peak performance of aftertreatment

In Green NCAP, a vehicle is defined as a hybrid electric vehicle when it is equipped with a propulsion battery of at least 60 V and is capable of driving with a minimum velocity of 10 km/h in pure electric mode. A “Not Off-Vehicle Charging Hybrid Electric Vehicle” (NOVC-HEV) is a hybrid vehicle that cannot be charged from an external source (will further be called HEV); “Off-Vehicle Charging Hybrid Electric Vehicle” (OVC-HEV) is a hybrid that can be charged from an external source and is more commonly referred to as PHEV (Plug-In Hybrid Electric Vehicle). Green NCAP’s test matrix for PHEVs consider the standard test matrix for ICE vehicles and HEV when the vehicle is working in CS (Charge Sustaining) mode with the addition of the following tests done in CD (Charge Depleting) mode: WLTC+ CD Sequence, PEMS+ Cold, PEMS+ Eco and PEMS+ Heavy. Tests in CD mode start with the HV (High Voltage) battery fully charged (100 % SoC). All constituents and energy use figures are measured in both CS and CD mode. The WLTC+ CD Sequence consists of driving the vehicle over the WLTC+ test starting with the HV battery at 100 % SoC. The requirements of the test are the same as of the WLTC+ Cold test. The vehicle is driven over multiple WLTC+ tests in a row until it reaches the CS condition, that is, the electric energy balance of all REESS (Rechargeable Electric Energy Storage System) is less than 4 % over a WLTC+ cycle. This WLTC+ CD Sequence procedure is also used to determine the available battery capacity and the EAER (Equivalent All Electric Range). EAER stands for the total driving range attributable to the use of electricity from the REESS over the WLTC+ CD Sequence.

A PHEV vehicle can be driven the following way:

- CD mode: with the HV battery charged where the vehicle will prioritise, if the situation allows it, to be run predominantly in EV mode only activating the ICE in exceptional cases.
- CS mode: with the HV battery discharged where the vehicle acts like a NOVC-HEV, running predominantly the ICE. The hybrid management system decides the strategy to be followed, that is, when the power at the wheels is provided by the ICE or the electric motor or both.

PHEV’s CO_2 values as stated in the CoC, are derived by WLTP testing in CD conditions where the vehicle starts with the HV battery fully charged until it is depleted and the vehicle starts working as a NOVC-HEV mainly operating the ICE, referred to as the CS mode. The number of cycles performed until this condition is reached and the concept of the utility factors lead to the published CO_2 and fuel / energy consumption values found in the CoC.

With these considerations, the fuel consumption of a PHEV leads to a non-understandable value for the average consumer and a non-realistic value in many usage situations. Green NCAP’s test matrix pursues the goal to provide a more realistic fuel and electric energy consumption by testing under more representative conditions and post-processing the results in a more sensible way. Furthermore, useful information on the different modes the PHEV can be driven in, is presented, showing the fuel and energy consumption separately as well as tailpipe emissions in both CS and CD modes.

2.2 Rating Methodology

The Green NCAP rating system builds up on three indices: Clean Air, Energy Efficiency and Greenhouse Gas, representing the vehicle’s impact on “health”, “wallet” and “planet” respectively. They are equally weighted 1/3 to sum up to an “Overall Index”, on which the 0 to 5 stars rating is based. The number of stars and half-stars indicates the overall average performance in all three assessment areas. Each index scores a maximum of 10 points, depending on the vehicle's performance. The thresholds are the same for all powertrain types of category M1 and N1 and are independent of vehicle size, body style, mass (capped to 3.500 kg) or price.

The assessment currently only considers the emissions produced by the vehicle in operation: "Tank-to-Wheel” (TtW). The inclusion of a "Well-to-Wheel" (WtW) based rating methodology and the presentation of an additional life cycle assessment (LCA) are among the next steps on Green NCAP’s roadmap.

The **Clean Air Index** is derived from pollutant emission constituents CO, NO_x and PN23 nm for all measurements and additionally NMHC (non-methane hydrocarbons) and the not yet limited NH_3 for the chassis dynamometer tests. The measurement results are converted into a score on a linear scale, except for PN23, for which a logarithmic scale is used. Zero is the lower end of the scale (i.e. high-performance threshold) where the maximum number of points is achieved. The upper emission threshold (i.e. low performance threshold), above which no or negative points are awarded, is derived from the legal Euro 6d limit, where between different values for positive ignition and compression ignition engines the lower one is chosen. The NH_3 upper threshold is set taking the 10 ppm Euro 6 heavy duty limit into consideration and after analysing already available measurement data. In addition to the upper threshold, there is a so-called "gross exceedance” threshold for each pollutant. This corresponds to 1,5 times the upper threshold, except PN23, which is by one order of magnitude higher. If any pollutant, with the exception of NH_3, exceeds its gross exceedance threshold, the score for that test is set to zero, regardless of the performance of the other pollutants. The pollutant thresholds for the PEMS+ tests are higher than those of the chassis dynamometer tests by a conformity factor of 1,32. The WLTC+ CAT (Cold Ambient Temperature) test is an exception of the lab tests. It is subject to rating with extended boundaries, which are the same as the upper thresholds for the PEMS+ tests, see Tab. 3

Tab. 3 Clean Air Index: rated pollutants and their thresholds.

Pollutant mg/km	Lower threshold	All chassis dynamometer tests (WLTC+ CAT)		On-road tests, CF: 1,32	
		Upper threshold	Gross exceedance	Upper	Gross
NMHC	0	58 (77)	87 (115)	-	-
NO_x	0	60 (79)	90 (119)	79	119
NH_3	0	10 (13)	15 (20)	-	-
CO	0	500 (660)	750 (990)	660	990
PN23 #/km	0	6E+11 (7,9E+11)	6E+12 (6E+12)	7,9E+11	6E+12

For the PEMS+ Congestion test, only NO_x is part of the assessment and the upper thresholds are as follows: 0,5 mg/s for average output and 1 mg/s for peak output. In that test, a score of 1 point is awarded for each of the two cases, when NO_x emission rates are less than the prescribed maximum.

The **Energy Efficiency Index** evaluates the vehicle’s energy consumption. For this purpose, liquid and gaseous fuel consumption is first converted into energy, using the unit kWh/100km. A linear scale is used to determine the indices. In this case, the lower threshold (maximum score for minimum energy expenditure) is not zero but 30 kWh/100km since all vehicles require a certain amount of energy to move. The lower threshold corresponds to 3,5 L/100km petrol or 3,1 L/100km diesel. Electric cars’ consumption is based on the energy amount taken from the grid. The upper threshold, above which no points are awarded, is 90 kWh/100km. These thresholds are chosen to reflect the typical range of energy consumption of modern vehicles and to achieve a certain resolution of the results. The upper threshold was obtained from ADAC Ecotest statistics back in 2018 after determining the Gauss curve of fuel energy consumption from more than 100 Ecotest results. [11] The lower threshold has been arbitrarily chosen after having analysed typical BEV and HEV energy consumption publications. The energy efficiency is rated only for the chassis dynamometer tests since the real-world consumption at the PEMS+ tests is not yet suitable for rating purposes due to variability and repeatability issues.

The **Greenhouse Gas Index** includes CO_2, CH_4 and N_2O. The scoring is done in the same way as for the pollutants in the Clean Air Index. The upper CO_2 threshold for zero points is based on the fleet average of the vehicles tested in the ADAC Ecotest until 2019 - 175 mg/km. N_2O is not regulated in Europe and CH_4 is only indirectly limited by Euro 6, but not as a GHG. The upper threshold for N_2O - 6,2 mg/km, is derived from the FTP75 limit in the US legislation. The upper threshold of 32 mg/km for CH_4 corresponds to the subtraction of the NMHC positive ignition Euro 6d limit from the corresponding THC (Total Hydrocarbons) limit. For WLTC+ CAT, the upper N_2O and CH_4 thresholds are 1,6 times higher than those for the other tests.

The currently available N_2O and CH_4 on-road measurement apparatus are not yet suitable for use in the frame of the programme, so greenhouse gases are not rated for PEMS+ tests.

Specifics of the PHEV Rating

For PHEV, each index scores are calculated in both CD and CS mode and combined. The contribution of results in each mode is determined by the obtained EAER. The higher the EAER, the lower the influence of the results in CS mode and the other way round, see Tab. 4.

Tab. 4 CS/CD determining ratings for PHEV.

PHEV	CD mode	CS mode
If EAER is ≥ 100 km	80 %	20 %
If 25 km ≤ EAER ≤ 100 km	Sliding Scales	
If EAER is ≤ 25 km	20 %	80 %

3 Measurement Equipment

For the chassis dyno tests, a test system equipped with a chassis dynamometer and emission measurement system is required. The test cell shall be able to reliably control the ambient temperature down to the required -7 °C WLTC+ CAT test. The accuracy of the chassis dyno force transducer shall be at least ±10 N for all measured increments.

For the emission measurements, a full flow exhaust dilution system for phase and test results is necessary. Both bag and continuous values allowing modal data sampling on a second-by-second basis are used. The constituents are measured with standard analysers for the purposes of vehicle emissions testing, however, the analysis of N_2O and NH_3 adds to the specifications. For those species an external device for raw ex-haust gas measurement may be used (e.g. FTIR (Fourier-Transform Infrared Spec-troscopy), QCL (Quantum Cascade Laser) or NDIR (Nondispersive Infrared Sensor) for N_2O). A reliable method or device for exhaust flow measurement, in the cases where some of the emissions are measured in the raw exhaust gas, is required.

For the on-road tests standard PEMS (Portable Emissions Measurement System) are used, the measured constituents are CO_2, CO, NO_x, NO, NO_2 and PN23. The initiative to measure N_2O and NH_3 also on-road failed, due to the experienced immaturity of market available N_2O PEMS, which seemed to be highly inaccurate at that time.

The **number of sub-23nm particles** (10 nm cut-off, also called PN10) is measured by some members in the scope of additional research activities. The apparatus used are listed in Tab. 5.

Tab. 5 Sub-23nm (PN10) measurement equipment used for research activities.

PN10	Empa	UTAC	IDIADA
Dyno	TSI CPC 3010-D Series equip. VPR Prototype equip.	HORIBA MEXA-2010 SPCS	AIRMODUS CPC
PEMS+	-	-	HORIBA OBS-ONE PN (10 nm) Prototype

Several methods for **hydrogen consumption measurement** are known but the requirements for safety, installation simplicity and precision significantly cut the list of possibilities. Moreover, the target is to determine not only cycle or test phase consumption but also continuous flow, both at chassis dyno and on-road testing. The chosen method is an in-situ flow-measurement between the tanks and the fuel cell via a Coriolis principle-based flowmeter (Emerson CMFS015, Coriolis Elite Sensor; 1/6 inch). The device is safely installed in a protected free space under the chassis and the cabin air is continuously monitored for the presence of H_2. Alternatively, the working principle of a fuel cell allows the determination of the H_2 consumption through the measurement of the stack's electric current output. This method can deliver high precision but is limited by the unknown H_2 purge flow. The analysis proved the expectation of that loss to be up to 5 % of the total flow and the electric current method can be seen as safe and cost-efficient alternative with a slight disadvantage in accuracy.

For all tests, suitable power analysers are needed. Here the exact requirements depend on the powertrain type – from conventional 12 V onboard systems to high voltage electric vehicles.

4 Tested Vehicles

Three pillars form the fundament of the vehicle selection for Green NCAP's tests:

1. Best-selling vehicles
2. Important market segments
3. Alternative drivetrain systems and new technologies

All tested vehicles have up-to-date emissions class (Euro 6d TEMP or Euro 6d). The selected vehicles were the current model year and were run-in over a distance between 3.000 km and 30.000 km. Two Round-Robin vehicles were used to check and ensure the repeatability of testing across seven European laboratories. Tab. 6 visualises the selection scheme for the first test run in Green NCAP.

Tab. 6 Scheme of Green NCAP’s vehicle selection.

Verification Vehicles (2 tests)	**Best selling vehicles** (21 tests)	**Important market segments** (15 tests)		**Alternative drive systems and new technologies** (13 tests)
1 test Diesel Round-Robin-Vehicle	**21 tests** selection of the **best-selling vehicle models** with the most popular engine version in Europe – all manufacturers with registration numbers >100.000	**3 tests** segment: **city** **most popular cars**	**supermini** **petrol**	**5 tests** **hybrid (HEV+PHEV)**
		3 tests segment: **business** **most popular cars**	**large family class** **diesel**	**4 tests** **electric (BEV)**
1 test Petrol Round-Robin-Vehicle		**3 tests** segment: **lifestyle** **most popular cars**	**supermini SUV** **petrol**	**2 tests** **natural gas (CNG)**
		3 tests segment: **most popular SUV**	**SUV** **diesel** 4WD	**2 tests** **innovation** most innovative drive systems
		3 tests segment: **transportation** **most popular cars**	**transporter** **diesel**	

5 Results

5.1 Vehicle Test Results

This chapter handles the results of the investigations conducted in the “Green Vehicle Index” (GVI) research project [9]. This section also presents PHEV results both in CD and CS mode. The only chassis dynamometer test conducted in CD mode is “WLTC+ Cold 1”. It is artificially derived as an average of the WLTC+ CD Sequence conducted for depleting the battery until CS mode is reached and is not comparable to a single test starting with a fully charged battery. For the PEMS+ tests of PHEV in CD mode, CD means that the test is started with the HV battery fully charged. The routes of all labs were approximately 85 km, so the on-road results of the PHEV tests in CD mode are comparable from the perspective of accumulated distance. PEMS+ tests in CS mode start with a HV battery state of charge (SoC) as established at the end of the WLTC+ CD Sequence.

5.1.1 Pollutant Emissions

5.1.1.1 Carbon Monoxide Emissions (CO)

Carbon monoxide (CO) is produced by incomplete combustion of the carbon-containing fuel as a result of a local lack of oxygen. The oxidation of carbon monoxide is temperature dependent. With decreasing temperature, the post-oxidation is slowed down and thus the CO emissions are increased compared to higher temperatures. [12] Due to the general excess air operation, a diesel engine generally has low engine-out CO emissions that are further oxidised together with HC in the DOC (Diesel Oxidation Catalyst) reactions.

For a petrol engine, mixture enrichment (air-fuel ratio lower than λ=1) also leads to relatively lower oxygen contents of the exhaust gas, which would be necessary to convert CO and HC to CO_2 in the TWC (Three-Way Catalyst). The evaporation effect of excessive fuel injected into the combustion chamber leads to lower exhaust and in-cylinder temperatures. This effect is actively used in engine management control strategies to cool down and control the exhaust valve temperature, avoiding excess temperature of the turbine, the oxygen sensor, the TWC and other exhaust components, as well as to compensate for the exothermal reactions in the TWC. However, this temperature decreasing effect is obtained to the detriment of higher CO emissions, in some cases of excessive PN emissions and obviously having adverse effects on life-time fuel consumption.

The light-off temperature for the oxidation of CO and hydrocarbons is 170-200 °C. These temperature limits still depend on the catalyst materials used and on the flow rate and the composition of the exhaust gas. In order to achieve a good conversion of CO and HC within a diesel oxidation catalyst, minimum operation temperatures in the range of 200-250 °C are necessary. [13]

Under low and medium engine load conditions, the measured CO emissions were below the Euro 6d limits, both at lab and real-world testing, see Fig. 2. Diesel powertrains emitted very low CO amounts even under severe conditions – the “worst” diesel CO emissions were 361 mg/km at WLTC+ CAT, whereas the average emitted by the tested diesel fleet for all lab tests was just 137 mg/km. Real-world CO values for those vehicles were even less. The results of the petrol vehicles, however, were partly surprising and for a couple of them – highly disappointing. While at WLTC+ Cold and Warm the results were well below the upper thresholds, in the -7 °C WLTC+ CAT test, 6 out of 36 petrol vehicles and one PHEV in CS mode exceeded 1.000 mg/km. It is creditable that even under these unfavourable conditions, most vehicles were still very efficiently controlling CO, some of them were even at the range 100-200 mg/km and those were also mainly the same cars, which kept the good conversion performance even under BAB130’s high engine load conditions. This motorway simulating driving test imposes a highly demanding engine load/speed profile to vehicles due to the abiding full load accelerations and forced some petrol vehicles into fuel enrichment. Fig. 3 compares the CO emissions behaviour of a high and low CO emitting petrol vehicle over the BAB130 test cycle and identifies the low lambda value at the acceleration phases as the reason for this high pollutant output. A very similar behaviour was also observed for the rest of the high CO emitting petrol engine vehicles. In the BAB130 test, 7 pure ICE petrol models, 2 PHEVs in CS mode and 1 HEV violated the upper CO threshold with results up to 9.992 mg/km. The PEMS+ Heavy test also includes high engine load accelerations and was also very challenging for these CO outliers. Here, PHEVs in CD mode also exceeded the threshold.

These findings show that some manufacturers still implement different fuelling strategies for engine operation areas inside and outside the typical WLTC and RDE engine operation ranges. In Green NCAP’s assessment such results are reflected by lower or even negative scores. However, most of the competitors demonstrate that CO is not a problem and can be sufficiently controlled even under extreme conditions.

All spark ignited engine powertrains have similarly increasing CO at short urban driving trips with cold engine start. Here, improved technologies for faster heat-up of the exhaust aftertreatment system and preventing cooling down of the exhaust temperature under the light-off temperature in idling would be helpful.

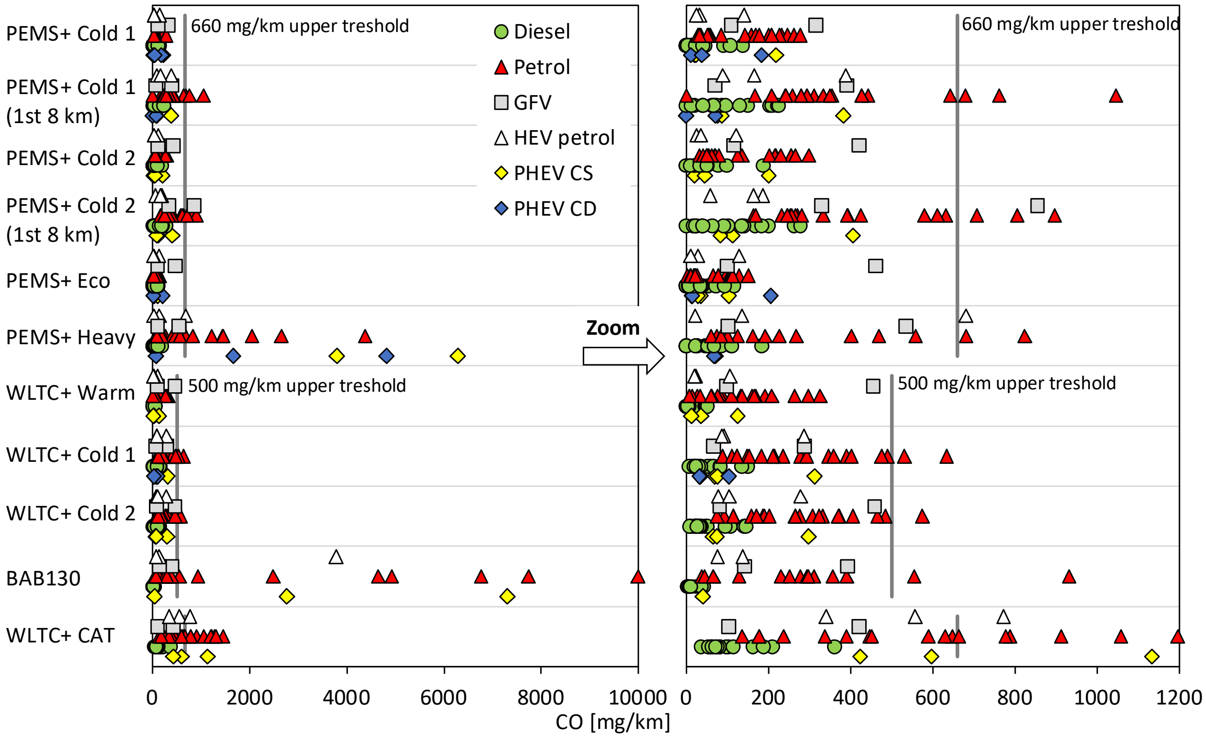

Fig. 2 Carbon monoxide emissions of the tested vehicles.

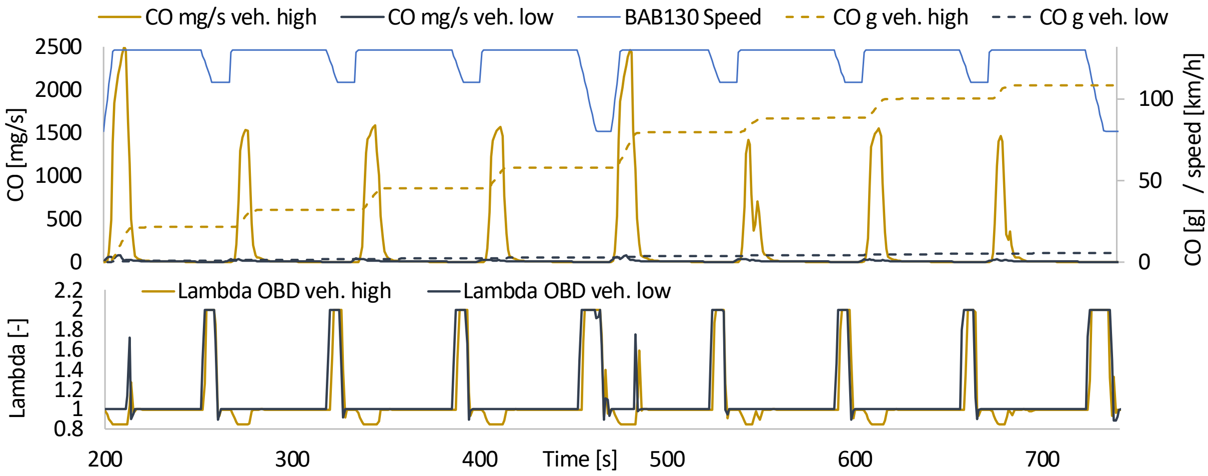

Fig. 3 CO emissions and air-fuel ratio (lambda) of a high and low CO emitting petrol vehicle at the BAB130 test. The low emitting vehicle achieves a result of 298 mg/km CO over the test cycle, the high emitting – 6.767 mg/km.

5.1.1.2 Non-Methane Hydrocarbon Emissions (NMHC)

Hydrocarbon (HC) emissions are a product of incomplete combustion. Unburnt HC species are formed in local oxygen-poor areas, or in zones that are not or only poorly affected by the flame front, meaning that local flame extinguishing plays an important role here. Overall, however, the diesel engine has low HC emissions due to the over-stoichiometric operation and compression ignition principle, while petrol engines are much more likely to have issues with that pollutant. The aftertreatment of HC emissions takes place together with that of CO in the DOC for compression ignition and in the TWC for spark ignition engines, the necessary temperature conditions are similar. [13]

Green NCAP differentiates between NMHC and CH_4. These substances are subject of analysis only for chassis dynamometer tests, since no measurement apparatus are commonly available for on-road testing. Diesel vehicles experience no difficulties in NMHC handling, at WLTC+ Cold they emitted on average just 4 mg/km. The highest measured result was 53 mg/km at WLTC+ CAT and this was by an order of magnitude higher than the results of most other diesel vehicles. At BAB130, diesel powertrains can be considered, with a couple of exceptions, as almost free of NMHC emissions.

In general, NMHC emissions are more of a consideration for petrol powered vehicles. At the WLTC+ Cold test, they emitted on average 18 mg/km and this result was quite consistent across the different models. At BAB130, the high temperature of the TWC guaranteed almost full conversion and the average of the petrol fleet was only 7 mg/km. One exception was found being at a level of 66 mg/km. This precise model also showed the same unfavourable behaviour for CO, 932 mg/km. This was a compact car of sporty character and performed BAB130’s accelerations with a maximum engine speed of 4.500 rpm at the 110-130 km/h and 6.000 rpm at the two 80-130 km/h accelerations. It was again the WLTC+ CAT test, where some vehicles proved cleaner than others. Approximately half of the models remained under the extended upper threshold of 77 mg/km, the other half exceeded it, whereas the highest output was 214 mg/km. The results were continuously rising from the best to the worst performing petrol vehicle and no extreme cases were found. GFV models’ NMHC were naturally close to zero.

The analysis of the WLTC+ CAT NMHC emissions proved the expectation that the pollutants are almost completely arising from the cold start phase and are eliminated as soon as the TWC reaches its light-off temperature. For example, at the worst observed case of 214 mg/km, 92 % of the total cycle NMHC output occurred within the first 100 seconds.

5.1.1.3 Nitrogen Oxides Emissions (NO_x)

The nitrogen oxide emissions of ICE equipped cars, especially those of diesel powertrains, are certainly one of the hottest discussion topics around modern vehicles. Fig. 4 shows the NO_x results of the tested vehicles at the different tests.

In the WLTC+ cycles at an ambient temperature of 14 °C, the NO_x emissions of all vehicles stayed below the upper Green NCAP thresholds (equal to the lowest of the Euro 6d legal limits (petrol: 60 mg/km; diesel: 80 mg/km)). However, there are significant differences between petrol and diesel technologies. With an average of 12 mg/km, petrol vehicles emit approx. a third of the diesel vehicles’ NO_x, which resulted in 32 mg/km on average. The tests with a warm engine start (WLTC+ Warm) show lower NO_x emissions, meaning improved efficiency of the pollution control system during the first few minutes of the cycle. Under more demanding test conditions, some models and technologies reveal the limits of certain pollution control strategies.

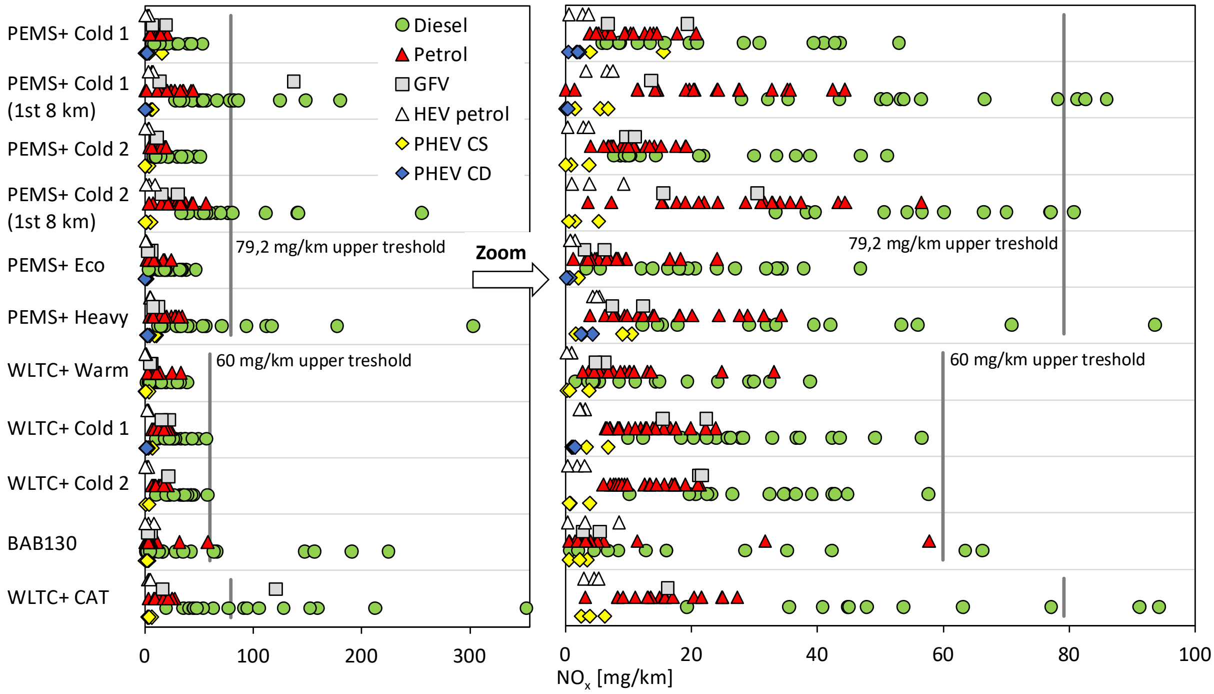

Fig. 4 NO$_x$ emissions of the tested vehicles.

The BAB130 cycle and PEMS+ Heavy test include several fully depressed pedal accelerations, high engine load accelerations and relatively high engine speeds. For a few vehicles, the emission levels increased notably under these circumstances. However, in general the tested fleet performed well and demonstrated robust behaviour, with a couple of exceptions. Among the diesel models, the good performers using LNT (Lean NO$_x$ Trap) + SCR (Selective Catalytic Reduction) technology or only SCR covering a large area of the engine calibration, showed stable and efficient de-NO$_x$ capabilities, even under highly demanding conditions.

As is generally known, there is a relationship between the power gradient experienced by the ICE engine and its NO$_x$ emission output. Fig. 5 depicts the NO$_x$ rate as a function of the v*a positive bins (v – velocity; a – acceleration). It clearly shows the increase in NO$_x$ emissions at higher v*a$_{pos}$ values. Moreover, the NO$_x$ emissions in a certain v*a$_{pos}$ bin can be dependent on the test mass. The orange line represents the PEMS+ Heavy test, with the highest payload, which results in significantly higher NO$_x$ emissions than the other trips, even in the same bin.

The heating strategy of the emission control system is a key element to optimise NO$_x$ reduction. A couple of diesel vehicles struggled at this test and emitted more than 100 mg/km, where the worst result was 350 mg/km. That can be seen as a proof that there is still room for optimisation of the aftertreatment performance and enhancement of its robustness and also for the legislator to lay down concrete measures and limits to reduce NO$_x$ at low ambient temperatures sub +8 °C. However, it should be noted that even under these severe conditions, most vehicles perform reasonably well.

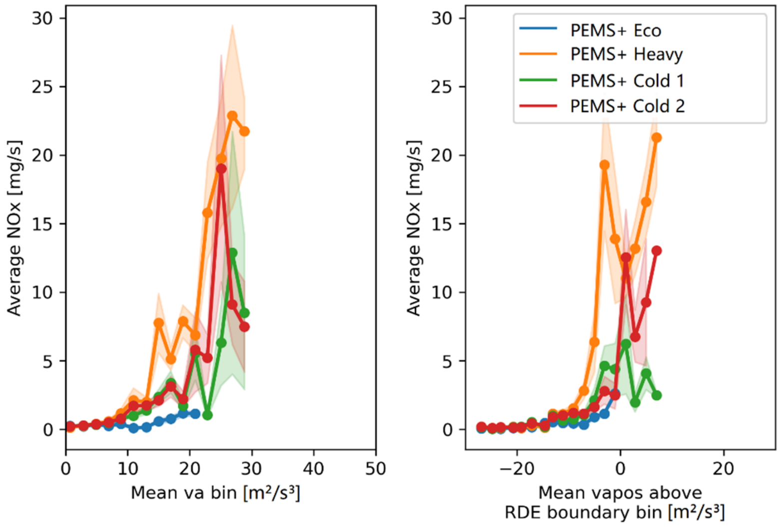

Fig. 5 NO$_x$ rate as a function of the v*a$_{pos}$ bins and comparison of the mean v*a$_{pos}$ with RDE regulatory boundary bin for different Green NCAP on-road tests.

At the PEMS+ Cold test, which starts with a cold engine, on average the NO$_x$ emissions were only 14,8 mg/km. Although the PEMS+ tests are carried out on the road and therefore are sensible to – amongst others – the weather and traffic conditions, the results are similar between the tests PEMS+ Cold and WLTC+ Cold, meaning that the tested vehicles generally were able to transfer their NO$_x$ emissions performance from the controlled lab environment to the real-world road testing.

Definitely, with an expected NO$_x$ value in the range of 0-8 mg/km, the winners in this part of the assessment are the hybrid vehicles. They manage to control the pollutant emissions even better than the pure petrol ICE powertrains and are rewarded for their robustness.

5.1.1.4 Cold Engine Start – Impact on the NO$_x$ Emissions

For pollutant emissions, the cold engine start and subsequent warming up of engine and emission abatement system need effective and efficient pollution reduction systems, such as TWC and SCR systems. Therefore, within Green NCAP more detailed analyses are done with regard to cold start emission performance. The behaviour at the short urban trips (first 8 kilometres of the PEMS+ Cold tests magnified) is separately reflected in the rating system. To determine the magnitude of cold start emissions, the end of the cold start and warm-up period should be defined. This can be done by observing a certain number of driven kilometres, or to analyse the engine coolant or lubrication oil temperature. However, the coolant temperature is not necessarily indicative of the operation temperature of emission control systems. Moreover, the impact of duration and distance of the cold start and warm-up varies per pollutant. Therefore, in this analysis, the end of a cold start is investigated by looking at plateaus in emissions, e.g. in Fig. 6. The depicted vehicle is a modern diesel model. As can be seen, after 2,2 kilometres a plateau in NO$_x$ emissions occur. In these 2,2 km, 237 mg of NO$_x$ are emitted. After that, there is hardly any increase of emitted NO$_x$. The 237 mg of NO$_x$ can be seen as an offset due to cold start.

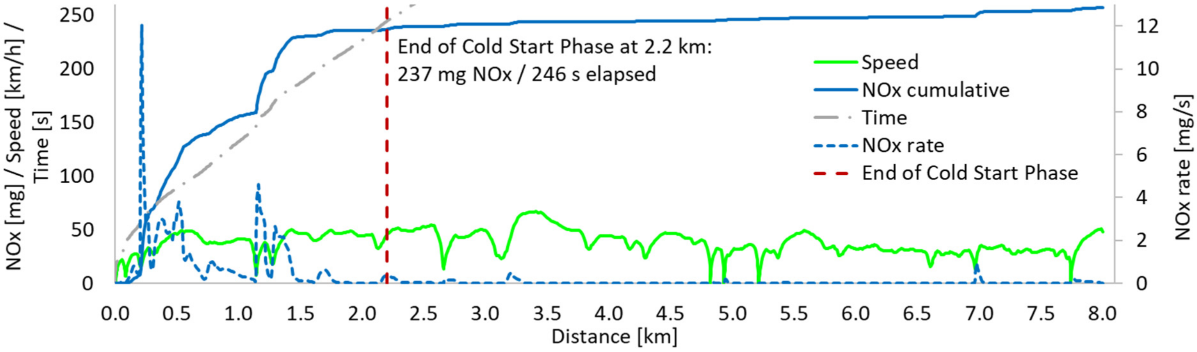

Fig. 6 Impact of the cold engine start on the NO_x emissions in the PEMS+ Cold test for a large family diesel vehicle.

Fig. 7 illustrates that diesel vehicles can have high NO_x emissions during cold start. On average, around 400 mg is emitted until a diesel vehicle is warm, but the range is 100 to 900 mg. The distance driven until the end of the cold start is for most diesel vehicles between 1 and 4 kilometres. The impact of cold start for diesel vehicles is substantially higher compared to petrol vehicles, but there are examples where both powertrain types are comparable. In general, the emitted NO_x is much lower for petrol vehicles, in most cases lower than 180 mg. Moreover, the majority of petrol vehicles are already warmed within the first 500 meters of the trip.

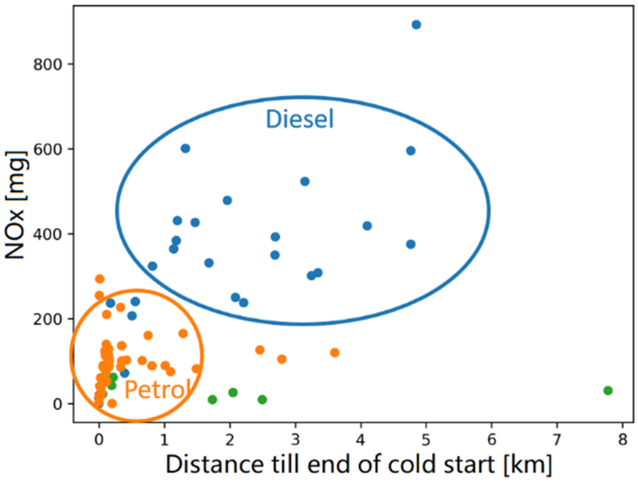

Fig. 7 Petrol and diesel vehicles' cumulated NO_x emissions at the time, when the end of the cold start phase of PEMS+ Cold is reached, displayed over the distance travelled until the end of that phase

5.1.1.5 Extensive Idling – Impact on the NO_x Emissions

During a valid RDE trip, according to Point 9.2 of Annex IIIA to Regulation (EU) 2017/1151 [5], if a vehicle idles continuously for a period of more than 180 s, the emissions during this period may be excluded from the evaluation. In practice, this means that for periods longer than this, all emissions are unregulated. Start-stop systems are often available to prevent extended idling. However, a start-stop system can be switched off, and does not work under all conditions, especially in winter or with high climatisation demand. Therefore, these circumstances present a risk for elevated emissions in real world and are part of Green NCAP's focus.

When the engine of a vehicle is warm, the exhaust temperature of the vehicle drops during idling. In contrast to that, a vehicle started with a cold engine will increase the exhaust temperature during idling. Most exhaust aftertreatment systems, such as SCR, catalysts and exhaust sensors, operate most effectively at temperatures which may not be reached or maintained during extended idling.

The tested vehicles showed variations in extensive continuous idling behaviour (>10 minutes). Despite these variations, two general idling characteristic pictures were observed:

1. Emissions remaining low throughout the entire idling period.
2. Emissions that are initially low and then begin to increase. The duration before the emissions' increase was not consistent across vehicles that showed this behaviour.

In some cases, the idling emissions can be substantial. Examples are available of vehicles where 15 minutes of idling caused about 50 % of the cumulative NO_x emissions during an RDE trip of nearly 2 hours, see Fig. 8. It should, however, be mentioned that in this test the start-stop system is deliberately deactivated. An active start-stop system would have prevented these emissions under normal conditions. There are also examples of very low idling emissions but, in general, this aspect is something to be considered in future powertrain developments.

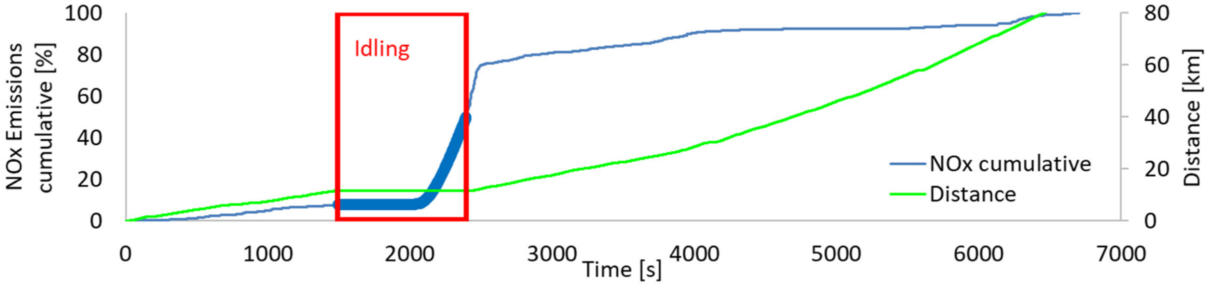

Fig. 8 Cumulative NO_x emissions in a PEMS+ Eco test for a large diesel vehicle with focus on the 15 min idling phase

5.1.1.6 PN23 Particle Number Emissions (PN23, Cut-Off Size: 23 nm)

The measurements showed, that PN23 emissions generally are no longer a major problem of ICE vehicles equipped with state-of-the-art emission control. However, it has to be noted that the results shown below do not include regenerations of particle filters. Especially the adverse effects of DPF (Diesel Particulate Filter) regenerations could clearly be observed and are caused by the generally lower exhaust temperature in a diesel exhaust aftertreatment system. [14] This circumstance results in the necessity of frequent, active DPF regenerations compared to the continuous passive GPF (Gasoline Particulate Filter) regenerations. Nevertheless, it was an encouraging observation that many vehicles stayed well below the upper threshold of 6E+11 #/km even with regeneration occurring during the test. Tests with DPF regeneration are considered invalid and excluded from Green NCAP's rating, unless very frequent regenerations with moderate PN impact are part of the aftertreatment strategy or tests without regeneration are difficult to obtain.

Already the average of PN23 emitted in in WLTC+ Cold shows, that the very low particle emissions of most diesel vehicles (1,1E+10 #/km) could not be matched by petrol vehicles (2,2E+11 #/km). General statements on CNG vehicles are difficult to make, since only two of such type were tested. From those two anecdotal samples, it could be observed, that one vehicle emitted a low number of particles while it was operated on its primary fuel. The second vehicle exhibited slightly higher PN23 emissions. It should be noted though, that this vehicle had previously been repaired to prevent excessive lubrication oil usage. After replacing its piston rings, the vehicle had been run-in for another 3.000 km and did not show again the excessive lubrication oil consumption that was determined before the repair.

Taking a closer look at Fig. 9, it is obvious that especially for diesel vehicles, high engine power requirements are not increasing PN23 emissions. The vehicles with petrol engines emitted slightly more particles than under light to medium part-load operation, but still undercut the upper threshold of 6E+11 #/km on the dynamometer and respectively, 7,9E+11 #/km in PEMS+ tests. A different picture emerges under cold start conditions. While diesel vehicles mostly remained below the upper thresholds, a small number of petrol vehicles went beyond. This effect can clearly be seen during the first eight kilometres of the two PEMS+ cold start tests and the WLTC+ CAT test. HEVs represent a special case since the combustion engine often has to run in higher engine load operation immediately after being started, which in some cases led to higher PN23 emissions than conventional petrol vehicles. Nonetheless, it should be noted that (with the exception of 1 HEV and 1 PHEV) HEVs, PHEVs and also the CNG vehicles tested were not equipped with a GPF, despite the fact that they complied with the Euro6d TEMP level.

The highest PN23 emissions (2,7E+12 #/km) were emitted by a petrol vehicle without a GPF and with MPFI (Multi Point Fuel Injection). While the PN23 emissions fall sharply after cold start for all vehicles with a particulate filter system, this effect cannot be observed here – the emissions remain on a very high level during the whole test cycle. Generally, -7 °C ambient temperature at WLTC+ CAT caused an increase of more than 50 % on average compared to a WLTC+ Cold at 14 °C, which in numbers means 2,6E+11 total average for all drivetrain types. A detailed look per drivetrain setup underpins this observation. While low ambient temperatures have a significantly increasing effect on PN23 emissions, this could not be definitely observed for high engine load tests. For all drivetrain setups, the average PN23 values emitted during BAB130 cycle were comparable to the emissions during WLTC+ Cold measurements or even lower.

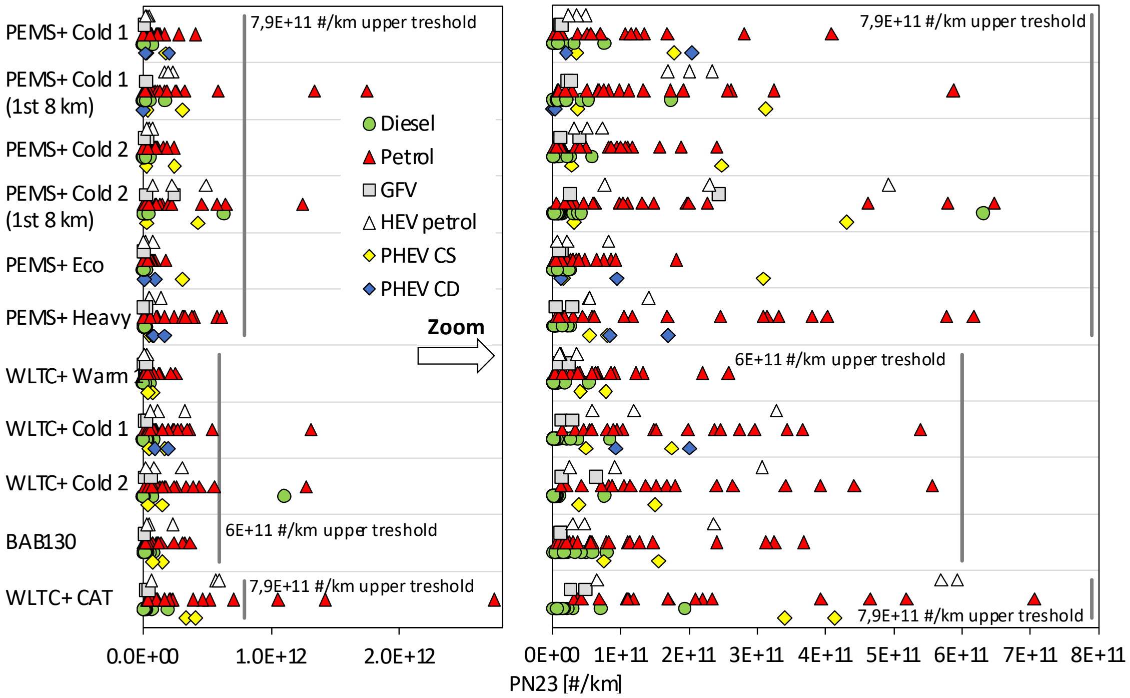

Fig. 9 PN23 emissions of the tested vehicles.

5.1.1.7 Sub-23nm Particle Number Emissions (PN10, Cut-Off Size: ~10 nm)

PN10 research was additionally conducted with the target on obtaining deeper insights of particle emissions of ICE equipped vehicles and to gain a clearer picture of the gap between PN10 and PN23. Three laboratories conducted this research, see Tab. 5 for details.

The following plots show the PN10 and PN23 results at the chassis dynamometer tests. For most vehicles two measurements are displayed – a first test and its repetition. The full-sized bar represents the PN23 measurement results and the faded grey colour depicts the PN10 add-up (i.e. the difference between PN10 and PN23).

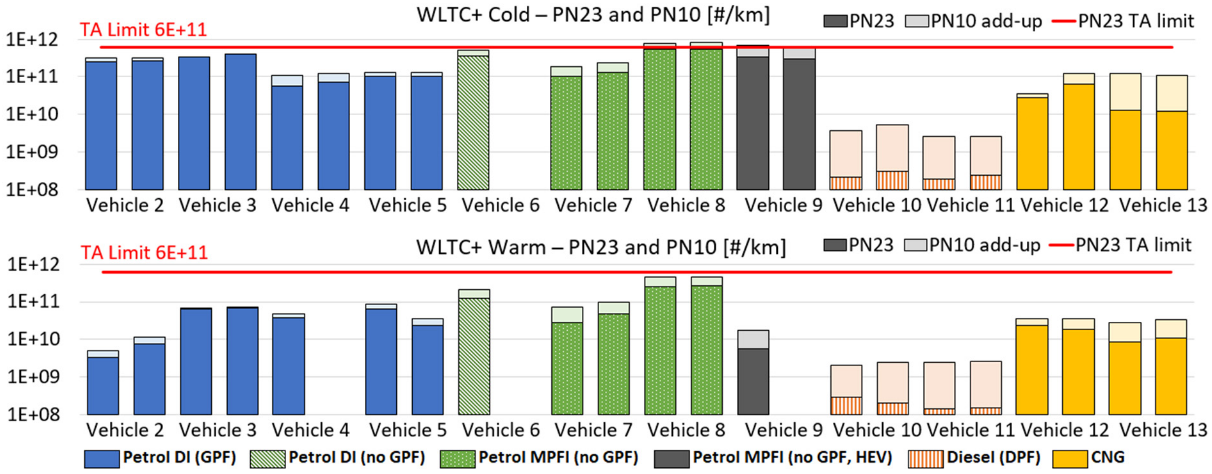

Fig. 10 Comparison of PN10 and PN23 emissions of different tested vehicles at WLTC+ Cold and WLTC+ Warm; 6E+11 represents the Green NCAP upper threshold (same as the type-approval limit).

From the results over WLTC+ Cold and WLTC+ Warm tests shown in Fig. 10, the following conclusions can be drawn. A common pattern, as expected, was that PN emissions were lower when starting the vehicle in warm rather than in cold conditions. On the one hand, petrol vehicles without a GPF observed in the WLTC+ Cold test tended to be close to the type-approval limit of 6E+11 #/km, equal to the Green NCAP upper threshold, or even above when measuring sub-23 nm particle sizes. The gap between PN10 and PN23 in the WLTC+ Warm test is higher for petrol vehicles without GPF than for those equipped with one. The reason might be the good GPF efficiency for sub-23 nm particles.

On the other hand, diesel vehicles emitted significant number of particles with a size below 23 nm, although the absolute values were on a much lower level than for other propulsion technologies. Diesel's PN23 emissions in particular, were so low that values close to the background PN levels (around 2E+08 #/km) were reached. PN10 emissions, however, were up to 17 times higher than PN23 (meaning around 2,5 – 6,5 E+09 #/km PN10). The two measured CNG vehicle's PN10 emissions were significantly higher than PN23. In particular, vehicle 13 emitted 1E+11 #/km more PN10 than PN23 and the difference was by one order of magnitude. Please note, that this was the vehicle previously repaired to prevent excessive lubrication oil consumption.

PN10 was measured in the WLTC+ CAT test at -7 °C ambient temperature, on a total of six vehicles. From the results shown Fig. 11, it can be seen that there was a significant increase in the particle number emitted by all types of vehicles, as it is expected under these severe conditions. For diesel and CNG vehicles, there were significant deviations found between PN23 and PN10 emissions (between 2 and 6 times more sub-23 nm particles). On the other hand, there was no significant difference between PN23 and PN10 seen for the measured petrol vehicles. This might be caused by the combustion conditions of petrol at this low intake temperature, inducing a large portion of large-sized particles only.

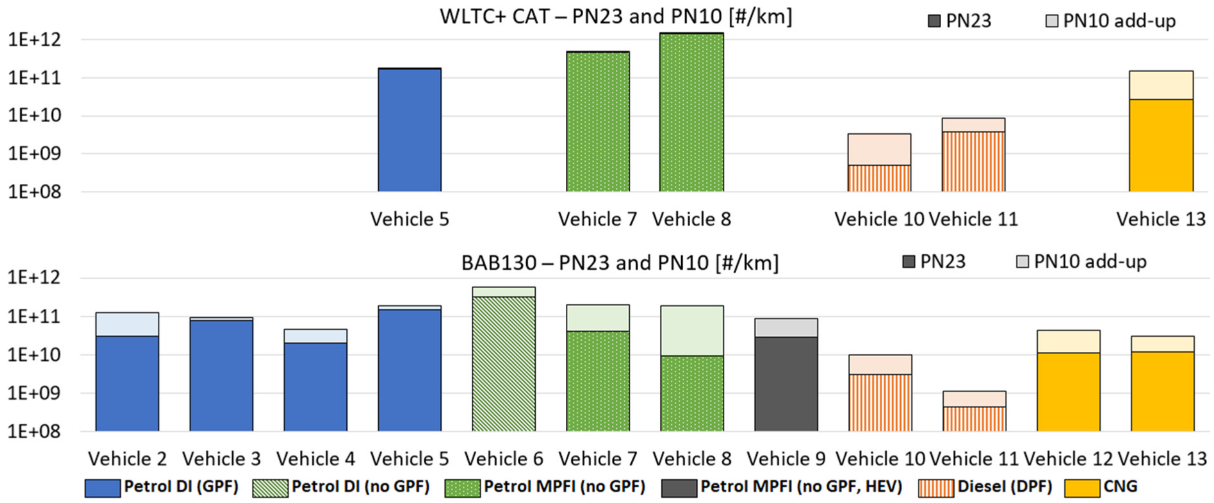

Fig. 11 Comparison of PN10 and PN23 emissions of different tested vehicles at the WLTC+ CAT (-7 °C test) and BAB130 tests.

The results in the case of the BAB130 test are shown in the lower part of Fig. 11. Due to high load conditions, the total particles emitted were significantly higher than in the conventional WLTC+ tests. In addition, for petrol vehicles the differences between PN10 and PN23 were generally higher than at the other test cycles, especially for the MPFI vehicles without GPF (i.e. vehicles 7 and 8 Fig. 11).

From the test conducted on the chassis dyno can be concluded that the propulsion technology with the smallest difference of PN10 compared to PN23 are petrol cars equipped with GPF, followed by petrol models without a filter. In addition to that, there is less variability between the vehicles and tests in regard to this difference. Nevertheless, these vehicles have the highest PN emissions overall. On the other hand, the technologies, where the gap between PN10 and PN23 is highest are diesel propelled vehicles. However, it is important to highlight that in general the absolute PN emissions are lower.

Under real-world testing conditions a total number of four vehicles was tested. Although the sample of vehicles is small, the trends in real-world emissions are similar to the findings under laboratory conditions.

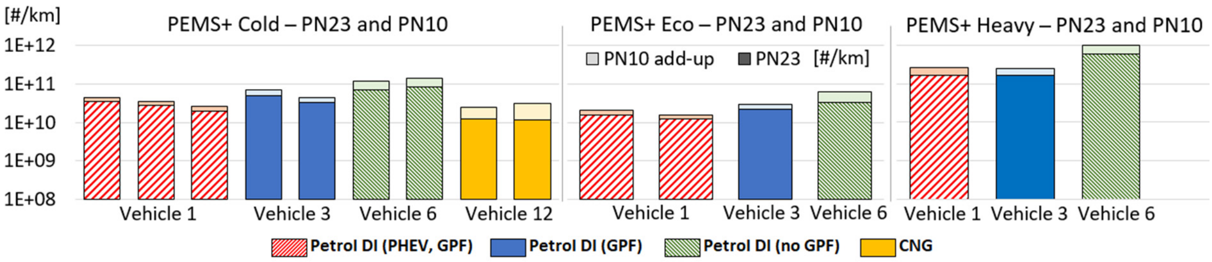

Fig. 12 Comparison of PN10 and PN23 emissions of different tested vehicles at on-road tests – PEMS+ Cold, PEMS+ Eco and PEMS+ Heavy.

As seen in the plots in Fig. 12, the petrol vehicle without GPF (vehicle 6) has higher total PN emission levels than the other vehicles. Moreover, it tends to show a higher difference between PN10 and PN23 than petrol with GPF. The vehicles tested have less overall PN emissions in PEMS+ Cold than in WLTC+ Cold in laboratory conditions. The PN emissions in PEMS+ Eco are lower and higher in PEMS+ Heavy than in PEMS+ Cold.

5.1.1.8 Ammonia Emissions (NH_3)

Ammonia is considered an environmental pollutant and a toxic compound for human health. Additionaly, it is notably associated with the formation of ultra fine particles and the acidification of rainwater [15]. Its formation in vehicle applications is not related to the combustion process but is caused by the chemical reactions in some pollution control cytalysts.

In diesel powertrains, two technologies use ammonia to treat nitrogen oxides. SCR technology uses urea as a reactive agent. Injected upstream of the SCR catalyst, under the effect of high temperatures, it decomposes into NH_3 and CO_2 to participate in the reduction of NO_x.

In recent years, combined SCR and lean NO_x trap (LNT) technologies have made their appearance in the automotive sector. In this hybrid design, the LNT catalyst stores NO_x in the lean phase and reduces them during the rich fuelling phase. During this latter mentioned phase, a quantity of NH_3 is produced and then adsorbed by the downstream SCR catalyst. Thus, during the next NO_x treatment cycle, even if the LNT catalyst is saturated, the NH_3 contained in the SCR allows the NO_x reduction. This technology limits the size of the LNT system while improving the overall reduction capacity.

The NH_3 results obtained with the GreenNCAP protocol are displayed in Fig. 13.

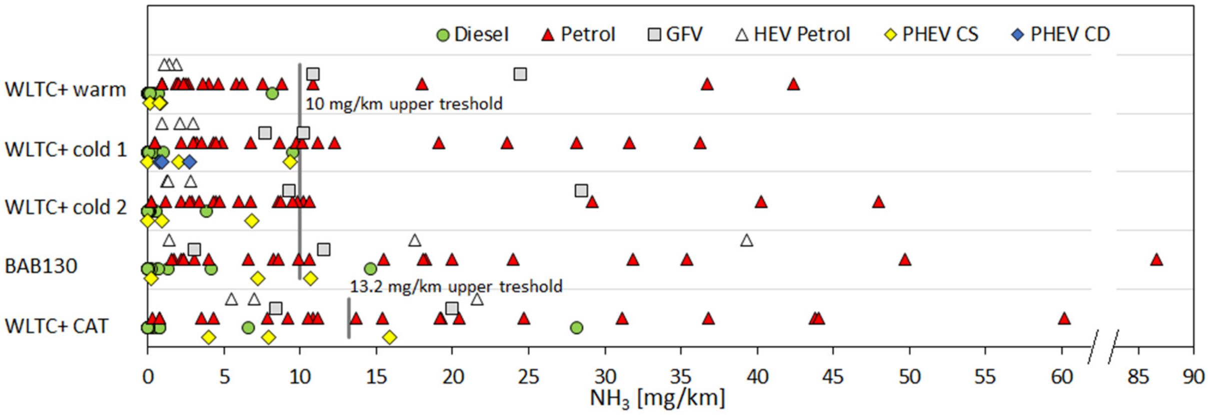

Fig. 13 NH_3 emissions of the tested vehicles.

Diesel models, which use ammonia as a reagent to reduce NO_x, showed extremely low NH_3 emission levels. Even unfavourable conditions and low ambient temperatures like at WLTC+ CAT did not provoke significant increase of NH_3. The worst average of the NH_3 emissions through all the chassis dyno tests was 11,5 mg/km, the next better results was 5,6 mg/km, whereas the third bad emitter put out only 1,4 mg/km on average. The rest of the vehicles emit NH_3 close to 0 mg/km. These results mean that in current SCR systems, the reagent is properly dosed and converted and NH_3 slip control is adequate.

Unfortunately, these observations do not apply to all petrol vehicles. Although their NH_3 output was on average below the upper threshold, many vehicles showed much higher emission levels. Different studies [15],[16],[17] have shown that rich air-fuel mixture operating conditions increase the NH_3 formation in a TWC. The same conditions are also favourable for the CO production, see chapter 5.1.1.1. These observations explain in some cases the high concentration of CO and NH_3 in challenging cycles like the BAB130 test, where fuel enrichment may be commanded by the engine management. The tests revealed that cold conditions also lead to an NH_3 increase. On average, in WLTC+ Cold, the petrol vehicles emitted 10 mg/km NH_3, 17 mg/km in BAB130 and 18 mg/km in WLTC+ CAT. However, the high disparity of the concentration between the tests shows that technical solutions exist to protect the exhaust components while limiting the NH_3 production.

The hybrid models showed in some cases noticeable emissions of NH_3 despite the functioning of the vehicle in full electric mode during short periods. These observations can be mainly explained by the several phases with deactivated ICE, which tend to reduce the temperature of the aftertreatment system. [17]

Thus, some vehicles clearly emit very high levels of NH_3, showing the importance of introducing a legal limit and controlling NH_3 emissions in future type-approval tests.

5.1.2 Greenhouse Gas Emissions

5.1.2.1 Nitrous Oxide Emissions (N_2O)

Nitrous oxide, also known as dinitrogen oxide or laughing gas, is a colourless gas with a slightly sweet smell and taste and, in combination with sufficient oxygen, practically non-toxic. Due to its long residence time in the atmosphere and its high global warming potential, which is 298 times higher than that of CO_2 [18], N_2O is consequently also regulated in the Kyoto Protocol as a greenhouse gas that requires significant reduction. So far, N_2O emissions are neither considered in the vehicle carbon footprint nor is this substance subject to any limit in the EU. Due to the lack of affordable and reliable on-road N_2O measurement equipment, the laughing gas emissions were analysed only in laboratory test cycles.

It was found that petrol and gas vehicles produce low, if any, N_2O emissions, independent of the test conditions. Laughing gas can be a non-desirable by-product of oxidation catalysts for petrol engines. According to detailed investigations on Pd-Rd catalysts, “The maximum of the N_2O formation is in the range of the light-off temperature of the catalyst” [19], whereby N_2O is formed at 200 to 450 °C in the presence of CO. On average, however, the Green NCAP tested petrol vehicles were measured to emit approx. only 1 mg/km of N_2O.

The mechanisms leading to the formation of N_2O in diesel powertrains are stronger due to the exhaust gas oxygen excess in combination with SCR systems. In addition to the favoured conversion of NO_x into N_2 and H_2O, a number of N_2O producing undesirable side reactions are to be expected, depending on the conditions [20]:

$$4\,NO + 4\,NH_3 + 3O_2 \leftrightarrow 4\,N_2O + 6\,H_2O \qquad \text{Eq. 1}$$

$$2\,NH_3 + 2\,O_2 \leftrightarrow N_2O + 3\,H_2O \qquad \text{Eq. 2}$$

$$8\,NO_2 + 6\,NH_3 \leftrightarrow 7\,N_2O + 9\,H_2O \qquad \text{Eq. 3}$$

Conventional catalysts tend to produce N_2O at temperatures above 400 °C. The reaction paths in Eq. 1, Eq. 2 and Eq. 3 are possible reasons for the formation of nitrous oxide. It shall be noted that Eq. 2 describes the direct oxidation of ammonia into N_2O and water. That reaction may happen at temperatures above 200 °C and hyper-stoi-chiometric air/fuel ratios in the exhaust gas. On the other hand, NO_2/NO_x ratio of 0,5 to be aimed for the best possible NH_3 conversion during the SCR process together with high temperatures above 400 °C, favour the reaction mechanisms in Eq. 1 and Eq. 3. The higher the temperature and NO_2/NO_x ratio, the higher will be the expected N_2O formation. Here Cu- and Fe-zeolite-based catalysts behave similarly, mixed oxide zeolites perform significantly better.

Platin containing DOC can also be the source of N_2O formation due to NO_x decomposition into NO, N and O and recombination to N_2O. Under dosing strategies which are relevant for the on-road operation, these mechanisms may be even dominant over the N_2O formation principles in the SCR.

Green NCAP's measurements proved that N_2O is a concern for diesel powertrains. Fig. 14 depicts the laughing gas emissions output from all tested vehicles in all tests. Almost all diesel powertrains emit more N_2O than the Green NCAP upper thresholds, which is the reason why their scoring points were adversely affected in this part of the assessment. On average, the number is 13 mg/km, which is an equivalent to almost 4 g/km of CO_2. At WLTC+ CAT, the average emission level is even clearly higher – approx. 18 mg/km. Surprisingly, in the dynamic BAB130 test, some vehicles showed less N_2O, which may be partly correlated to the higher NO_x emissions of some of them. However, a general statement about an interdependency between NO_x and N_2O is not possible here.

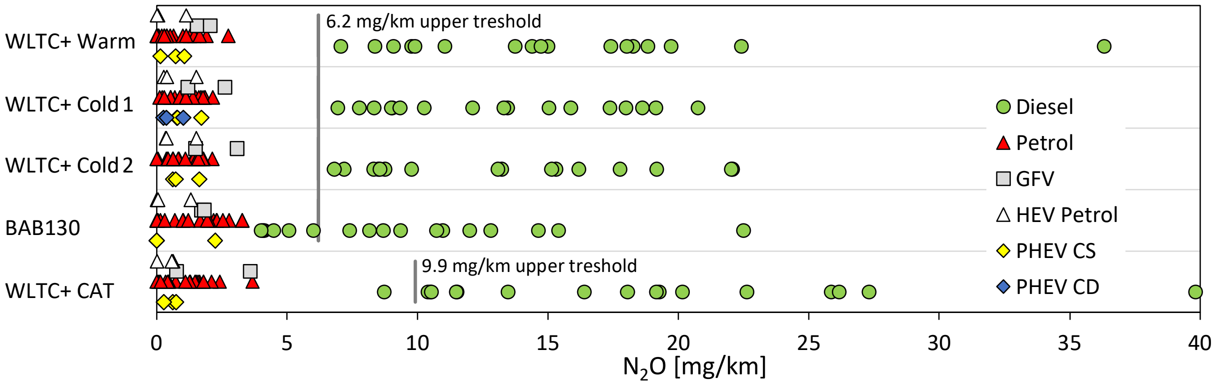

Fig. 14 N_2O emissions of the tested vehicles.

The behaviour of the N_2O emissions under WLTC+ CAT test conditions for a petrol and diesel car is compared in Fig. 15.

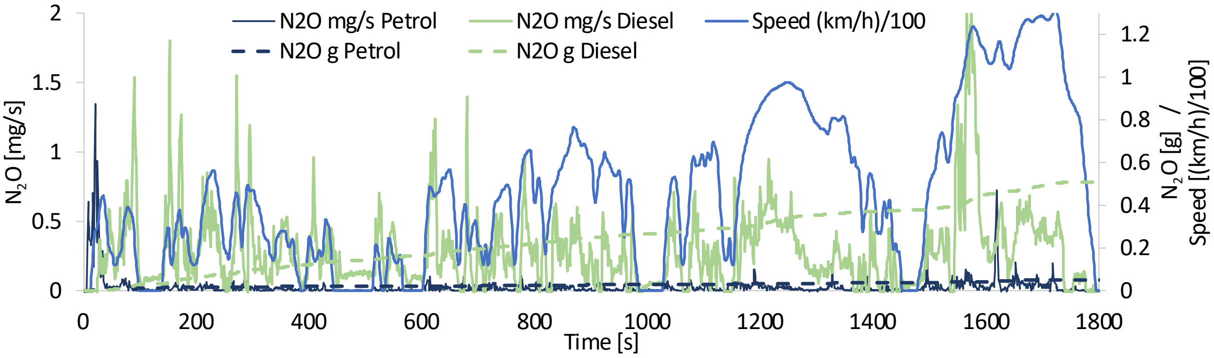

Fig. 15 N_2O emissions of a petrol and diesel vehicle in the WLTC+ CAT test. The petrol vehicle emits 1,6 mg/km, the diesel one – 20,1 mg/km.

Common between both powertrain types were high output peaks measured in the acceleration phases. The diesel powertrain, however, showed generally a much higher N_2O emissions output – by one order of magnitude. Here, N_2O is formed also during idling phases. High-power demand cycle phases (high and extra high) accelerate the nitrous oxide accumulation. While the cold start causes a high output for the petrol model and leads to the assumption that the thermal behaviour of the abatement system is predominant, for the diesel powertrain the conclusion is that the N_2O emissions correlate to engine load.

5.1.2.2 Methane Emissions (CH_4)

Green NCAP handles CH_4 as a greenhouse gas with a 25 times higher global warming potential than CO_2 (as set in [18]). Methane emissions were measured only under laboratory testing conditions, Fig. 16 summarises the results.

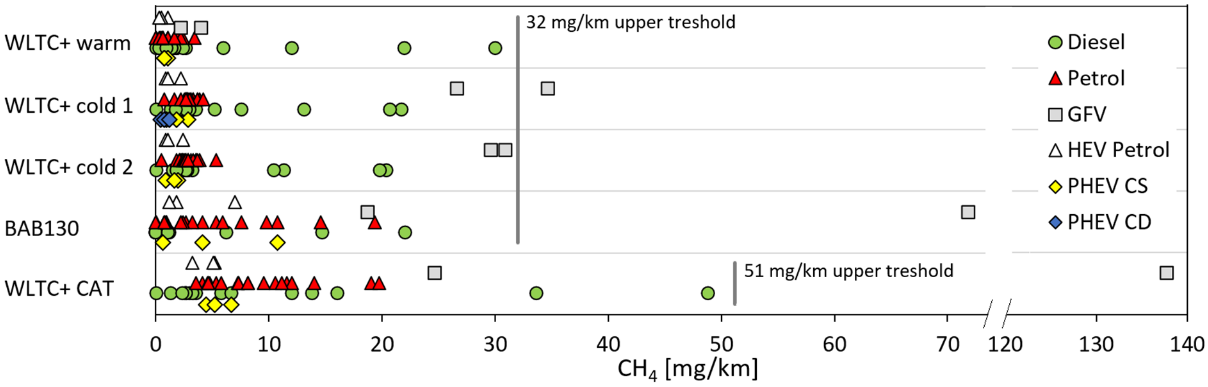

Fig. 16 Methane emissions of the tested vehicles

Petrol vehicles performed well, with the results starting at 0 and never exceeding 20 mg/km (corresponds to 0,5 g/km CO_2 equivalent).

Natural gas engines must still contend with the issue of methane slip, which is both a potent greenhouse gas as well as difficult to convert with the platin based TWC emissions aftertreatment, because CH_4 is significantly more stable than the other hydrocarbons in the exhaust gas. It requires temperatures above 400 °C for 50 % conversion, i.e. approx. 200 °C higher compared to petrol [21]. Different catalyst coatings result in different performances, which are dependent on the exhaust gas composition and temperature. The literature shows that for GFV catalysts the optimum between light-off temperature, lambda window and aging properties, is provided by catalyst coatings with a combination of Rhodium and Palladium. The optimum lambda window is on the slightly rich side – 0.98-0.99 [22]. The light-off temperature of modern TWC for GFV lay around 300-400 °C. Studies continue to explore new catalysts and synthesis techniques to address the challenges and improve conversion. Different precious metal combination and strategies, e.g. lean-rich cycling, can lower the light-off temperature and increase the conversion rate. But also alternative technologies like electrically heated catalysts and HC absorbers can provide viable solutions. [23],[24],[25]

Even though only 2 GFV were tested, the results were sufficient to identify largely different behaviour, Tab. 7. While vehicle A's aftertreatment managed to reduce the methane output under all testing conditions, vehicle B failed to do so at WLTC+ CAT and BAB130 tests. The analysis proved that none of the CNG vehicles was running on petrol at any lab test, the engines were started on CNG. This was not entirely the case for the on-road tests, where vehicle B started on petrol in the PEMS+ Cold tests before switching to gaseous fuel mode after approx. 2 minutes.

Tab. 7 Methane emissions of both tested CNG vehicles at different laboratory test cycles in mg/km.

CNG Vehicle	WLTC+ Cold	WLTC+ CAT	WLTC+ Warm	BAB130
A	26,6	24,6	4,0	18,8
B	34,7	137,7	2,1	71,8

Analyses the CH_4 phase output of the weaker performing GFV.

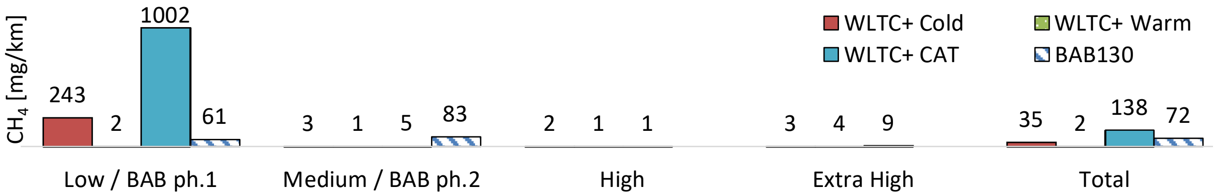

Fig. 17 Methane emissions of the weaker performing CNG vehicle B under the different test cycles and cycle phases.

It is obvious that in all tests, except BAB130, the methane emissions occur only at the first phase and are eliminated in the later phases, the reason for which is the necessary light-off and minimum conversion temperature of the TWC. In the WLTC+ CAT test, the CH_4 slip immediately after test start is significantly increased, which correspondingly results in a worse rating score for this part of the Greenhouse Gas Index. Moreover, the comparison with the low CH_4 emissions of vehicle A prove that methane slip should not be a problem even under -7 °C cold start and warming-up conditions. Vehicle B also emits high CH_4 amounts in both BAB130 test phases, which cannot be explained with low catalyst temperature anymore, since BAB130's test phases start after the powertrain has already passed the BAB130 preconditioning phase and is warmed up. However, the issue of replaced piston rings to reduce oil consumption of this vehicle should be mentioned again. As a result of this, despite running in the engine for more than 3.000 km, the TWC might still be chemically poisoned by lubrication oil additives.

5.1.2.3 Carbon Dioxide Emissions (CO_2)

Nowadays, carbon dioxide emissions are in the spotlight of most discussions surrounding modern mobility. There is a growing awareness that only the holistic assessment of the greenhouse gas emissions through the whole vehicle life cycle can describe accurately the vehicles impact with regard to climate stabilising objectives. However, European legislation, certification and taxation still are based on the local tailpipe CO_2 emissions. The CO_2 emissions of passenger cars are subject to regulation and monitoring. Regulation (EU) No 2019/631 [8] requires EU countries to record information for each new passenger car registered on their territory. The EEA indicator 'CO_2 performance of new passenger cars in Europe' shows a steady decline in emissions until 2016 but, since then, average emissions of new cars have been increasing, EEA claims. [26] The statistics show that in 2019, average CO_2 emissions of new passenger cars registered in the European Union, Iceland, Norway and the United Kingdom (UK) were 122,3 g/km in NEDC or 147,3 g/km in WLTP. [26] This figure (NEDC) is below the 2015-2019 target of 130 g/km but well above the 2020-2024 target of 95 g/km. According to the EEA analysis, several reasons have contributed to the increase in average CO_2 emissions related to average vehicle mass increase, including safety and the increase in comfort functions as well as the increasing demand for SUVs and other larger and heavier cars. The declining market share of cars equipped with a diesel engine through all vehicle segments [27] is another major reason for the rising CO_2 emissions. Vehicle mass is anticipated to further increase due to electrification and fitting of heavy propulsion batteries. This trend is anticipated to continue and partially offsets the efficiency gains achieved by electrification and recuperation of electric energy. Electric vehicles constituted 3,5 % of new car registrations in 2019. [26] However, light weighting of vehicles and reversing this adverse trend could help to significantly reduce CO_2 fleet emissions. [28]

The tailpipe CO_2 emissions of the Green NCAP tested vehicles are presented in Fig. 18. For the chassis dynamometer tests, results above the CO_2 emission upper thresh-old of 175 mg/km lead to negative points. WLTC+ Cold is the test cycle closest to the certification cycle and here the tested vehicles emitted an average of 143,5 g/km, which matches the average WLTP certification value from the CoC – 144 g/km. The WLTC+ Cold average for the petrol vehicles was 135,5 g/km, which was significantly lower than the diesel average of 158 g/km. The two GFV showed an average output of 118,5 g/km, whereas one of them was systematically better than most of the other conven-tional competitors. Here, the inherited CO_2 advantage of methane as fuel is visible. Two of the three HEVs performed outstanding at all tests, beating most of the other ICE equipped vehicles. One of them even reached 87 gCO_2/km at the PEMS+ Eco test.

The PHEVs tested with an “empty” battery in CS mode showed widely spread results – ranging from the lowest results among vehicles equipped with an ICE on-board up to the highest among them. These results prove that an uncharged PHEV can be seen as a very good hybrid vehicle in the best case but also as a high emitter, depending on the model and testing conditions. Based on the architecture, weight, properties of the electric components and operation strategy, some PHEVs could utilise their hybrid nature better than others. E.g. in PEMS+ Heavy in CS mode, one of the PHEV ended up with the worst measured CO_2 result at all, even higher than the large conventional diesel ICE vans. Regarding the performance in CD mode, similar conclusions can be drawn. In PEMS+ Heavy in CD mode, one PHEV made very little use of the battery and achieved results just a bit better than the heavy ICE vehicles. Another PHEV didn’t use its stored electricity at all and the final CO_2 values for CS and CD modes were fairly close.

For PHEV, the WLTC+ Cold is the only lab test in CD mode (it represents the average of the WLTC+ CD Sequence) and its outcome is taken into account in the rating, whereas neither PEMS+ CO_2 results nor PEMS+ energy consumption are reflected by the rating due to the variability and repeatability issues known for on-road testing.

Fig. 19 illustrates the reason for the counterintuitive higher CO_2 emissions of the diesel vehicles compared to the other powertrains. Nowadays, smaller and lighter vehicles are mainly propelled by petrol engines, whereas heavier vehicles still need the high torque and efficiency of the diesel aggregate. The better specific fuel consumption of the diesel engine is being offset by the mass of the vehicle, which leads to the results shown below. The offset of the diesel trendline from the petrol one is a good indication of the specific CO_2 emissions' (and consumption's) benefit of the diesel powertrains. The trend of CO_2 emissions increasing with the mass is obvious. According to the EEA [26], the average vehicle mass in 2019 was 1417 kg (mass in running order). The average test mass of the Green NCAP tested petrol vehicles was 1466 kg, that of the Diesel models was 1840 kg; petrol and diesel together – 1600 kg; all tested Green NCAP vehicles – 1634 kg.

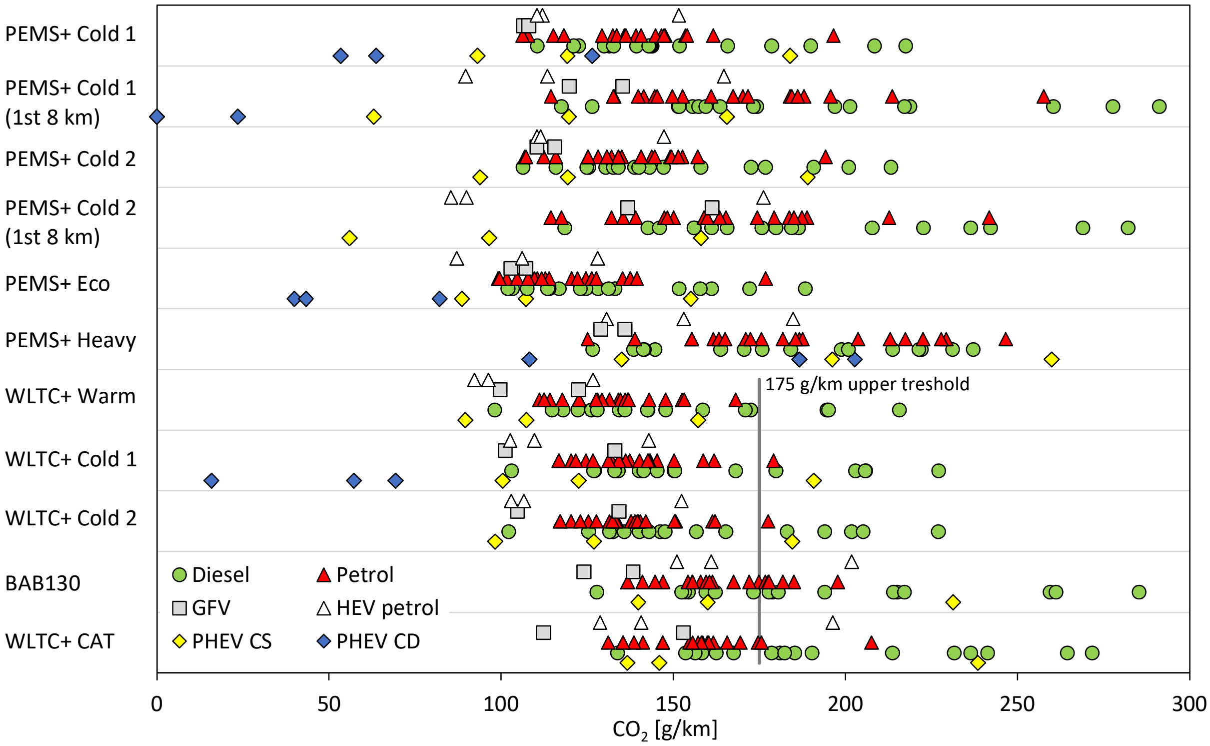

Fig. 18 Tailpipe CO2 emissions of the tested vehicles.

Fig. 19 also includes the CoC CO_2 values of the vehicles (except PHEV). A good correlation to the measured values is visible, despite the slightly different test conditions in the WLTC+ Cold test compared to type-approval WLTC.

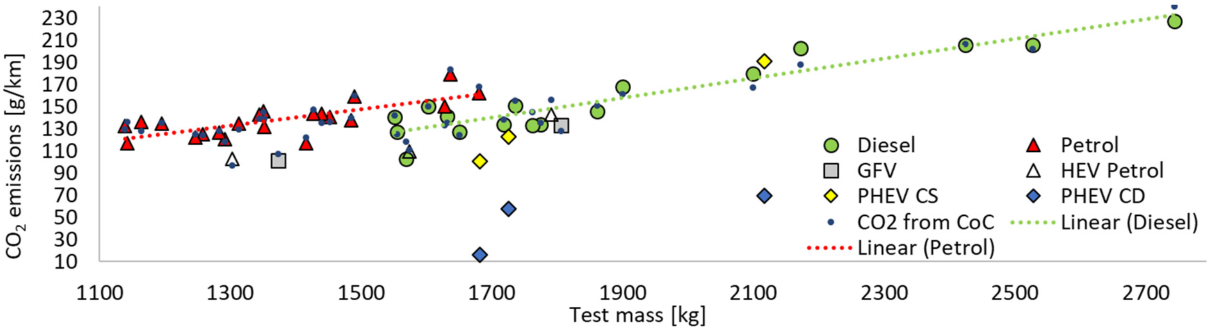

Fig. 19 CO_2 tailpipe emissions of the tested vehicles at WLTC+ Cold and CoC CO_2 values plotted against the vehicle test mass.

5.1.3 Energy Consumption

Fig. 20 depicts the energy consumption of all tested vehicles at all conducted tests. At and below the lower threshold of 30 kWh/100 km, the full score for this part of the assessment in the corresponding test is given.

In general, the BEVs (Battery Electric Vehicles) showed the lowest energy consumption. It is important to mention that the electricity consumption is considering the energy withdrawn from the grid, taking the charging and discharging losses into account. All three BEVs performed very efficiently under real-world testing and the differences between the PEMS+ test results were small. In the BAB130 test the electricity consumption notably increased. The highest energy demand was measured in the WLTC+ CAT test. Here, one of the BEVs consumed nearly 40 kW/h, meaning it needed twice the energy it consumed at WLTC+ Cold, while the other two BEVs increased the consumption by approximately 50 %. In conventional powertrains part of the excess heat produced by the ICE is used for cabin warming. For BEVs an additional heating system is needed, which withdraws valuable energy from the battery. The FCEV (Fuel Cell Electric Vehicle) couldn't match the energy consumption values of the BEV competitors but still performed well, especially under real-world testing. In the WLTC+ CAT and BAB130 tests, however, its energy consumption increased to levels in the lower range of ICE powertrains.

It is worth pointing out that in real-world conditions (PEMS+ Cold), the best performing of the three PHEVs needed only 27,7 kWh/100 km (2,3 L/100 km + 7,4 kWh/100 km) starting with a fully charged battery or 35,4 kWh/100 km in CS mode (4,1 L/100 km).

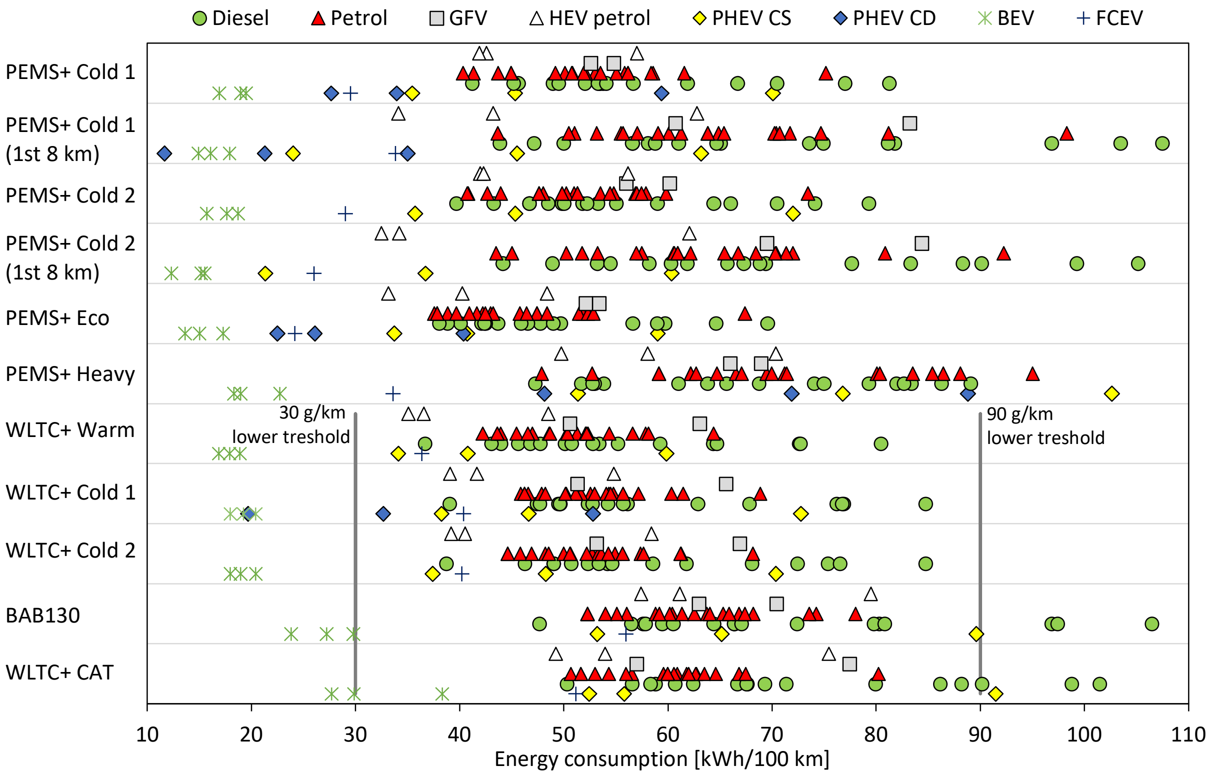

Fig. 20 Energy consumption of the tested vehicles.

Analogous to Fig. 19, Fig. 21 illustrates the energy consumption of the tested vehicles at the WLTC+ Cold test over the test mass. The BEV with test mass of approx. 1900 kg has excellent aerodynamic properties, which helped it keep its cycle consumption at a similar level as the other two BEVs despite the higher mass. It also is the newest of the three tested BEV models and had the best charging efficiency.

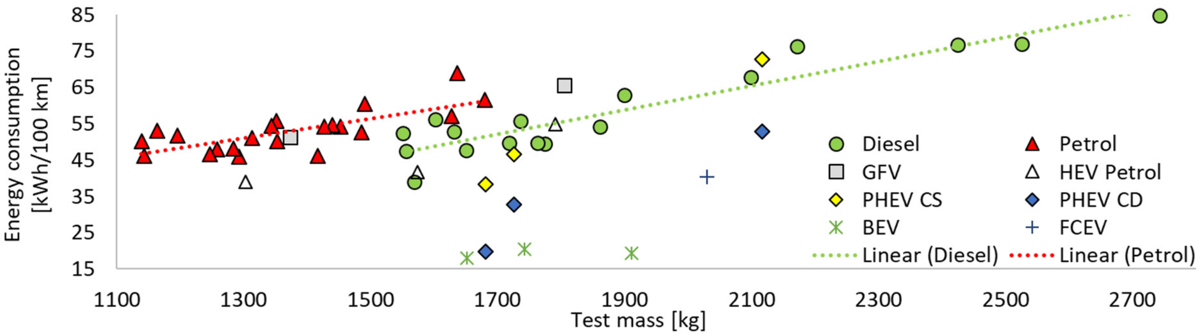

Fig. 21 Energy consumption values of the tested vehicles at WLTC+ Cold plotted against the vehicle test mass.

5.1.4 Plug-In Hybrid Electric Vehicles (PHEV) – Highlights

The PHEV technology and design of the three tested vehicles are very different and make it difficult to compare them with each other. The PHEVs have the potential of a better energy efficiency compared to conventional vehicles and this can be seen from the results of two of these vehicles. With regard to the energy consumption, in the more demanding tests BAB130, WLTC+ CAT and PEMS+ Heavy, one PHEV performed reasonably well, one behaved as a conventional vehicle and one (a heavy SUV) demonstrated a notably poor performance. Tab. 8 summarises some interesting PHEV results.

Tab. 8 Characteristic data and test results in CD mode of the three tested PHEVs.

PHEV Vehicle	WLTC+ CD Sequence Total Average Energy Consumption [kWh/100km]	WLTC+ cold CS Fuel Consumption [kWh/100km]	Test Mass [kg]:			
			CoC*	WLTC+ CD Sequence	PEMS+ Eco CD	PEMS+ Heavy CD
1	19.7 (0,7 L + 13,6 kWh)/ 100 km	38 (4,4 L/100 km)	1681	1681	1717	1756
2	52.8 (3,1 L + 26,4 kWh)/ 100 km	72,6 (8,4 L/ 100 km)	2117	2117	2178	2278
3	32.7 (2,6 L + 9,9 kWh)/ 100 km	46,7 (5,4 L/ 100 km)	1725	1725	1821	1885

* CoC p.47.1.1 "test mass"

PHEV Vehicle	System Power (ICE + EM) [kW]	Nominal Battery Capacity [kWh]	Electric Driving Range in CD Test:				
			Pure Electric Driving Range (km)			EAER (km)	
			WLTC+ CD Sequence	PEMS+ Eco CD	PEMS+ Heavy CD	WLTC+ CD Sequence	CoC
1	90	8,8	39,4	52,4	23,4	39,1	45
2	165	13,8	31,2	48,6	0,2	29,9	45
3	104	8,9	0	44	0	49,5	49

With PHEVs, the electric driving ranges are of special interest to the consumer. In Green NCAP two different values are considered – the pure electric driving range (meaning the distance in electric mode until the first time the ICE is activated) and the EAER. The numbers are obtained from the WLTC+ CD Sequence and the real-world tests (PEMS+) in CD mode. In one case the pure electric range was zero because the combustion engine started right from the beginning of the test cycle. The reason was the cabin heating demand. In two cases the EAER was in good correlation with the nominal value coming from the CoC but in one case it differed significantly, see Tab. 8.

The following special behaviours might occur at PHEV testing:

1) Cabin climatisation strategy activates the ICE during CD mode

During HV battery CD mode operation, the vehicle might not be able to work all the time with activated electric motor only and there might be some periods where the ICE is turned ON. This not for providing traction to the wheels but to heat up the cabin due to a climatisation request if the A/C is active. The ICE could be working under high idle conditions.

2) ICE powers the wheels during CD mode if high propulsion power is requested

The electric system might not able to supply all the requested propulsion power, so the ICE will also be activated to drive the wheels during some periods, even when the HV battery is fully charged.

5.1.5 Battery Electric Vehicles (BEV) – Highlights

The driving range and the energy efficiency are the most interesting aspects with regard to BEV testing. The electric vehicles follow the standard Green NCAP test matrix (same for ICE) and an additional battery test is performed to determine the available battery capacity, energy consumption with regard to the electricity withdrawn from the grid, the charging efficiency and the occurring charging losses.

The three tested BEVs can be classified in the segments B (supermini), C (small family car) and B-SUV. The declared nominal battery capacity of the three vehicles is 39, 51 and 58 kWh respectively, with driving ranges from 289 to 418 km. The test results, however, showed that these distances can only be reached under high energy saving driving conditions. The measurements revealed that approximately 81 % to 89 % of the electricity coming from the grid is available at the output side of the HV battery, when charging is conducted with the standard charger, meaning that there are significant energy losses between grid and wheels, which the consumer has to pay for but will not get transportation for in return.

The BAB130 test and the WLTC+ CAT together with the PEMS+ Heavy are the most demanding ones and can decrease the nominal driving range by more than 50 %, see Fig. 22. The energy consumption values (from the grid) in the WLTC+ Cold test ranges from 19,2, and 19,3 to 20,4 kWh/100 km.

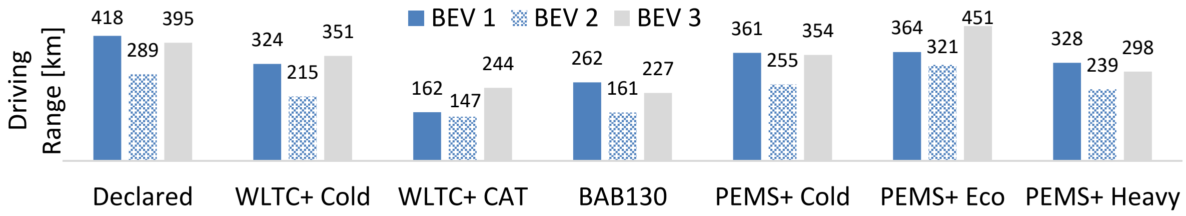

Fig. 22 Measured driving ranges of the three BEVs in different tests.

Nearly all tested BEVs reach the maximum score in the separate categories. Only one of them loses some points in the energy efficiency pillar due to the poorer performance in the WLTC+ CAT test.

5.2 Rating Results

The star rating is the easiest overall rating for consumers to understand expressed in 0 to 5 stars, combining the indices Clean Air, Energy Efficiency and Greenhouse Gas. Currently, all three indices are weighted equally, signifying equal importance to: health, which is affected by pollutant emissions; consumer spending and fuel/energy consumption, both influenced by a vehicle's energy efficiency as well as global warming, which is affected by greenhouse gases emitted. Optimising in one area to the detriment of another remains possible with these principles applied. However, poor performance in one part of the assessment will lower the average and result in a lower star rating.

Fig. 23 shows an overview of the overall ratings of all tested vehicles.

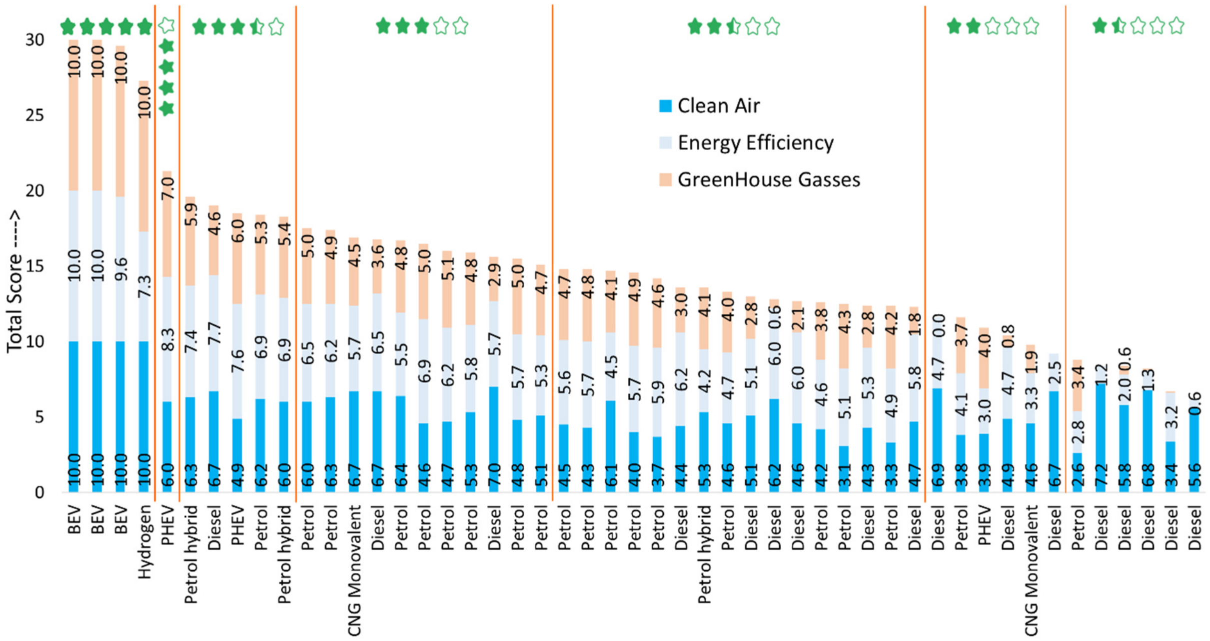

Fig. 23 Total score, index score and star rating of the tested vehicles.

Three BEVs and one FCEV were rated with 5 stars. During operation, they emit neither pollutants nor greenhouse gases at the tailpipe. The high efficiency of the electric motor leads to a low energy consumption. Due to the fact that it also consumes a relatively small amount of energy and emits only water, the hydrogen car is also rewarded 5 stars. The vehicle rated with 4 stars is a PHEV. Five vehicles, two of them are with conventional powertrains and two are HEVs, were rated with 3½ stars. Both conventional models have good exhaust aftertreatment, moderate mass and engine power.

Fig. 24 compares the index results of 39 tested cars with ICE, 23 of them with petrol (including HEV but excluding PHEV) and 16 with diesel engines.

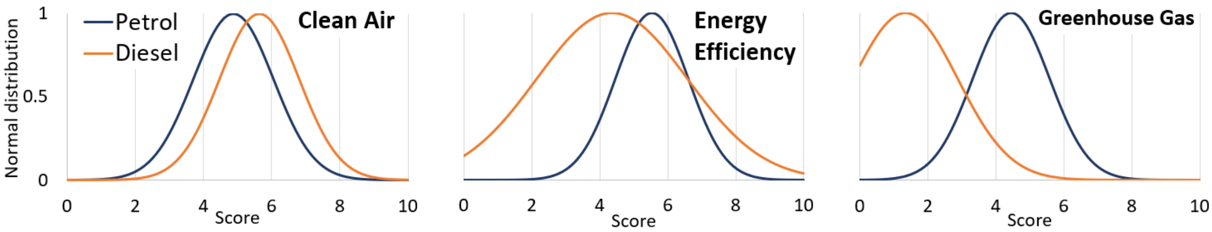

Fig. 24 Normal distribution of the index scores for the three rating categories "Clean Air Index", "Energy Efficiency Index" and "Greenhouse Gas Index". Differentiation between diesel and petrol powertrains (including HEV but excluding PHEV)

With regard to the Clean Air Index, the diesel vehicles generally scored better. This is mainly due to the great progress in diesel exhaust gas aftertreatment of the diesel vehicles complying with the latest Euro 6d TEMP and Euro 6d regulatory levels. Some of the diesels not only emitted low NO_x, but also fell below the PN23 upper threshold by several orders of magnitude. In contrast to that, several petrol vehicles, especially those equipped with MPFI, which do not have to comply with the Euro 6 PN limit value, were not equipped with particle filters. The same statement was valid for the two CNG vehicles, two of the HEVs and two of the PHEVs. The PN23 emissions of the petrol vehicles were on average about 10 times higher than those of the diesel vehicles.

The picture is different for the Energy Efficiency Index. Most petrol vehicles achieved an efficiency index between 4,5 and 6,5 points. For diesel vehicles, the results are further apart and are mostly between 2 and 6,5 points. One reason is that some of the diesel vehicles tested had a high mass. For vehicles with high mass and/or engine power, it becomes more difficult to minimise emissions and energy consumption at the same time. For three of the tested diesel models, the lower efficiency index is related to the utility value because they offer more than 5 seats and significantly higher transport capacity (big vans). However, the utility value is not a part of the Green NCAP assessment yet.

Petrol-powered vehicles also had an advantage in the Greenhouse Gas Index due to the lower vehicle mass. In addition to CO_2, diesel vehicles also emited more climate relevant nitrous oxide N_2O. The diesel engine is once again being installed primarily in large and heavy vehicles. For three diesel vehicles, the CO_2 specification according to CoC is already higher than 200 g/km. The three highest type-approval CO_2 values among the tested petrol vehicles were 183 g/km, 168 g/km and 160 g/km.

6 Discussion

Although the Green NCAP programme goes beyond the boundaries of environmental testing set out in legislative Approval and Roadworthiness testing, there are obviously still also limitations and constraints, mainly given by the Tank-to-Wheel approach, the available budget per car tested and the time it takes for a deep-dive analysis of a vehicle’s environmental performance. Other constraints are the unavailability of robust on-road PEMS equipment to measure non-regulated pollutants and GHG emissions, the absence of a useable, common engine load variable in OBD, the impact of DPF regenerations on the Clean Air Index and the absence of direct sampling points in electrified vehicles to determine important findings such as the significant energy losses over the on-board charger.

Addressing these issues requires continuous developments and investments, which the consortium has so far achieved by the members without the necessary involvement of other academia, the industry and NGO’s. However, these limitations and constraints can only be fully resolved by international collaboration and exchange of knowhow and experience with all stakeholders. This certainly includes consumers as the most important stakeholder for an independent test programme but also industry to mutually learn from the Green NCAP test results and from the innovations that hopefully follow in next technology generations.

The assessment currently only considers the emissions produced by the vehicle in operation: "Tank-to-Wheel” (TtW). The highest share of powertrains still is propelled by fossil generated energy. Among that share, the vehicle's driving behaviour impacting GHG emissions and pollutants is well depicted and the associated assumptions and assessments are plausible and robust. However, on a global scale, energy production and delivery from the fossil source to the filling station are also important: "Well-to-Wheel" (WtW) based analyses consider that fact. For electric vehicles, the CO_2 "mix" of electricity generation – renewable or coal-based – is important. The comparison of fossil vs. electrically powered vehicles is not meant to be provocative. As early as possible, Green NCAP therefore plans to change the assessment of greenhouse gases from TtW to WtW.

The ultimate target is a life cycle assessment (LCA), which is a high priority on Green NCAP's roadmap and work on this has already begun.

7 Conclusions

From the test results, it became clear that the impact of legislation is high on the vehicle's environmental performance. For example, the lack of legal requirements for diesel vehicles under cold ambient temperatures today results on average, in a weaker NO_x performance in the WLTC+ CAT test. In addition, emissions after a cold engine start, or during very high or low engine loads are a point of attention of future legislation. Petrol propelled vehicle propulsions escaping the need to fit a GPF, such as manifold-injected engines but also GFVs, HEVs and PHEVs, exhibit relatively high PN emissions. Non-regulated emissions constituents today, like the pollutant NH_3 for petrol engines and GHGs like N_2O for diesel engines, were in some test results also high. Hence, there is a need for the legislator to address these issues in the upcoming Euro 7 legislation and in the revision of the CO_2 / GHG fleet legislations. On the positive side, the impact of RDE real-world requirement introduction in legislation back in 2017 is an enormous success. The leap towards low NO_x and PN tailpipe emissions and its robustness under most driving and ambient conditions was confirmed by the Green NCAP test results.

Several paradigm changes can be observed within the presented results. On the one hand, there is the abolishment of the cliché "clean but thirsty petrol against economical but dirty diesel". It could be seen that in many cases diesel engine powered vehicles tend to emit lower levels of polluting exhaust gases, even in comparison to modern petrol vehicles (an important current limitation of the rating methodology, however, is that tests with DPF regeneration are excluded from the assessment). On the other hand, generally, within the tested vehicles, models equipped with petrol engines tend to consume less energy – a property which was traditionally reserved for diesel vehicles. Additionally, in the frame of Green NCAP's rating methodology, petrol vehicles receive a significantly higher Greenhouse Gas Index than diesel engines. Nowadays, it can be seen that both petrol and diesel vehicles can perform very well with regard to both fuel consumption and pollutant emissions. With modern emissions aftertreatment systems and new engine concepts, the differences between both propulsion types become significantly smaller. The observed improvements, however, come at a cost and it is certainly easy to notice that new small and low budget vehicles are mainly available with petrol powertrains because these are less cost intensive than the diesel ones. Large vehicles, however, still might need the high torque diesel engine, which naturally has a generally higher specific energy efficiency than petrol engines and offers that fast refuelling and large driving range that most electrified vehicles do not offer yet.

The tested PHEVs showed very different results and proved that a vehicle of this powertrain type is not necessarily an economical one. In fact, under unfavourable conditions one of the PHEVs showed fuel consumption values similar to big diesel vans. At the same time, in real-world conditions (PEMS+ Cold), the best performing of the three PHEVs needed only 27,7 kWh/100 km (2,3 L/100 km + 7,4 kWh/100 km) starting with a fully charged battery or 35,4 kWh/100km in CS mode (4,1 L/100 km).

The three tested BEVs made visible that demanding tests outside the type-approval conditions like the BAB130 and the WLTC+ CAT tests are building the biggest challenges for BEV with a reduction of the driving range by more than 50 %. Future BEV development should better address the efficiency of the cabin heating technology and the reduction of the charging losses. Nevertheless, within the current TtW based rating system, all the tested BEVs received the maximum score of 5 stars.

Due to its locally emission free powertrain, the tested FCEV achieves the full score in the Clean Air and Greenhouse Gas Indexes. Because of the efficiency losses of the fuel cell, where electricity is produced out of hydrogen, the powertrain cannot reach the efficiency of the BEVs yet but still gets a very creditable result of 7,3 points out of 10. With a high driving range and fast refuelling, FCEV vehicles would hold up a very good argument against the typical for BEVs range anxiety, once the hydrogen mobility network starts developing.

8 Outlook

One of Green NCAP’s main operational objectives is to provide evidence for the need of future legislative changes such as for the upcoming Euro 7 step, the revision of Roadworthiness legislation and for the CO_2 fleet legislation. At the same time, it is Green NCAP’s ambition to stay ahead of such regulatory requirements at the EU and UNECE levels. Green NCAP will regularly revise the test procedures so as to stay aligned with and to complement these important regulatory developments, ahead of regulatory application time. Like the safety programme, it is the intention of a mature Green NCAP programme to provide planning certainty to industry and other stakeholders. Green NCAP will continue to promote technology neutrality and investigate all propulsion and fuelling types available on the market.

The current flaw in the rating system that BEVs are automatically allocated a best 5-star rating, will be partially addressed by redesigning the GHG scoring pillar on a WtW basis. By implementing the WtW analysis into the GHG scoring pillar, Green NCAP aims to have a fairer comparison between the different propulsion performances and inform the consumer better on the environmental impact of the preferred car(s). It is definitely needed to increase resolution in the 5-star rating category to enable distinguishing between a good and badly performing electrified vehicle.

Green NCAP will continue breaking new grounds and will keep on pushing the technological boundaries, spark competition among manufacturers of vehicles, systems, components and measurement equipment as well as drive innovation.

8.1 Life Cycle Assessment

Based on the methodology of „Life Cycle Assessment" (LCA), an LCA Expert-Tool (Version 2.0) is developed and used by the international Automobile Clubs e.g. FIA, ADAC, ÖAMTC to assess the GHG emissions and the cumulated primary energy consumption of about 500 different transportation systems with a passenger vehicle using different fuels, propulsion systems and state of technologies in 40 countries.

The LCA-tool is now used to estimate the life cycle based results on GHG emissions (in CO_2-eq as sum of CO_2, CH_4 and N_2O) and the cumulated primary energy demand of the 50 vehicles tested and ranked by Green NCAP. The vehicles include ICE, HEV and PHEV using petrol and diesel with biofuel blending and CNG, FCEV and BEV with specific electricity generation mix for each European country. The initial results are discussed among the Mobility Clubs and their members.

The LCA results for each of the 50 vehicles are available online in a "Consumer Information Package" including the following information per kilometre and in the total life cycle over 200.000 km:

- Characteristic vehicle data
- GHG emissions in g CO_2-eq/km and tons per vehicle
- Primary energy demand in kWh/km and MWh per vehicle

The online results will be available in the first semester of 2022 on https://www.greenncap.com/

9 Acknowledgement

Green NCAP's members would like to thank the Green NCAP secretariat for their pivotal role having initiated the pilot programme and for their continued support and guidance on the road to a mature, independent consumer test programme of a vehicle's environmental performance.

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10 Abbreviations

A/C	Airconditioning

ADAC	Allgemeiner Deutscher Automobil-Club
BAB130	Bundesautobahn test
BASt	Bundesanstalt für Straßenwesen
BEV	Battery Electric Vehicle
CAT	Cold Ambient Temperature
CD	Charge Depleting
CF	Conformity Factor
CNG	Compressed Natural Gas
CoC	Certificate of Conformity
CS	Charge Sustaining
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EAER	Equivalent All Electric Range
EEA	European Environment Agency
EM	Electric Motor
Empa	Swiss Federal Laboratories for Materials Science and Technology
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FIA	International Automobile Federation
FTP75	US Federal Test Procedure
GFV	Gaseous Fueled Vehicle
GHG	Greenhouse Gas
GPF	Gasoline Particulate Filter
GSI	Gear Shift Indicator

GVI	Green Vehicle Index
HEV	Hybrid Electric Vehicle
HV	High Voltage
ICE	Internal Combustion Engine
IDIADA	Institut d'Investigació Aplicada de l'Automòbil
LCA	Life Cycle Assessment
LNT	Lean NOx Trap
MPFI	Multi Point Fuel Injection
NCAP	New Car Assessment Programme
NEDC	New European Driving Cycle
NGO	Non-Governmental Organisation
NMHC	Non-Methane Hydrocarbons
NOVC-HEV	Not Off-Vehicle Charging Hybrid Electric Vehicle
ÖAMTC	Österreichische Automobil-, Motorrad- und Touring Club
OBD	On-board diagnostics
OVC-HEV	Off-Vehicle Charging Hybrid Electric Vehicle
PEMS	Portable Emissions Measurement System
PHEV	Plug-In Hybrid Electric Vehicle
PN	Particle Number
PN10	Number of Particles with a size down to 10 nm
PN23	Number of Particles with a size down to 23 nm
RDE	Real Driving Emissions
REESS	Rechargeable Electric Energy Storage System
SCR	Selective Catalytic Reduction
SoC	State of Charge
SUV	Sports Utility Vehicles

THC	Total Hydrocarbons
TNO	Netherlands Organisation for Applied Scientific Research
TtW	Tank-to-Wheel
TWC	Three-Way Catalyst
UNECE	United Nations Economic Commission for Europe
UTAC	Union Technique de l'Automobile, du motocycle et du Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
WtW	Well-to-Wheel

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