Characterization of exhaust gas and particle emissions of modern gasoline, diesel and natural gas vehicles

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Abstract

Motor vehicle exhaust emissions could be sharply reduced within the past 20 years by the introduction of exhaust aftertreatment systems, modern engine control concepts and cleaner fuels. However, it has not been possible to significantly improve air quality in cities with regard to particulates and ozone in the past 10 years. It appears that the reduction in vehicle exhaust emissions achieved is offset by the growth in traffic as well as by changes in the composition of exhaust emissions and the corresponding reactivity in the environment. The reduction of selected pollutants therefore remains an important issue alongside greenhouse gas reduction. The present investigation illustrates the emissions of actual gasoline, diesel and natural gas passenger cars in the official European driving cycle and in the real-world driving cycle Artemis. The natural gas vehicles show the lowest impact on air quality.

Keywords: emissions, environment, passenger car

1 Introduction

Although vehicle exhaust emissions of air pollutants are generally decreasing, it has not been possible to reduce air quality problems in cities in the past 10 years [1]. In particular, the concentrations of particulates and ozone are too high, causing severe health effects. Besides improving the local air pollution situation, the reduction in global warming due to greenhouse gas emissions is of great importance for the mobility sector, in view of increasing worldwide mobility and demand for transportation. Finally, numerous established researchers are predicting bottlenecks in energy supply for the next few decades, pointing to the importance of clean biofuels.

The requirement for future motor vehicles is therefore very clear: emissions of toxic pollutants such as particulates and ozone precursors have to decrease to near zero, greenhouse gas emissions have to be reduced far more than in recent years and the introduction of biofuels has to be enabled on a large scale.

Exhaust emission measurements on motor vehicles are often performed using the official European driving cycle. This is a practical test cycle for type approval purposes, but allows limited comparability with real-world driving. Few exhaust gas and particulate emission data are available from modern motor vehicles representing a real-world driving pattern.

Empa therefore performed exhaust gas and particulate emission measurements on 32 gasoline vehicles with and without direct injection, diesel vehicles with and without particulate filter and natural gas vehicles. Both, the statutory official European driving cycle (Fig. 1) and the Artemis driving cycle CADC [2] (Fig. 2), which has been developed in the EU project Artemis, based on the statistical analysis of driving patterns in Europe, have been considered. The results are interpreted with regard to the actual air quality problems in cities (ozone and PM10) and with regard to greenhouse gases.

2 Experimental setup

2.1 Vehicles

All vehicles examined in this study have been certified according to Euro-4 regulations. They are series production vehicles currently in use by different owners. All vehicles were less than seven years old and had mileage lower than 100,000 km. All the vehicles have been thoroughly checked for possible technical defects prior to the measurements.

The experiments were conducted with commercial fuel (sulphur content less than 10 ppm) with the installed lubricating oil filter and commercial lubricating oil. The tests using the European driving cycle (Fig. 1) were started with cold engine after vehicle conditioning at 23 °C. The other tests using the real-world Common Artemis Driving Cycle CADC (Fig. 2) were started with warmed-up engines. There, the lubricating oil temperature was increased to a minimum of 80 °C by conditioning the vehicle on the chassis dynamometer prior to these tests.

The investigation included three market-available passenger cars powered by natural gas (CNG) from major European manufacturers. Their displacement ranged from 1.6 to 2.0 l. All CNG engines had a stoichiometric combustion layout. The gasoline vehicle sample comprised 19 passenger cars, 16 with port-injection (MPI) and 3 with direct-injection (DI) engine technology. Vehicles of European and Japanese manufacturers were included. The engine displacement of the MPI sample ranged from 1.2 to 3.9 l and ranged from 1.6 to 4.5 l for the DI sample. In addition, the tests included 12 diesel passenger cars of European and Japanese origin; whereas six of these vehicles had an OEM-fitted diesel particulate filter (DPF). The engines' displacements ranged from 1.2 to 2.2 l for the diesel sample without a DPF and from 1.2 to 3.7 l for the DPF-equipped diesel vehicles.

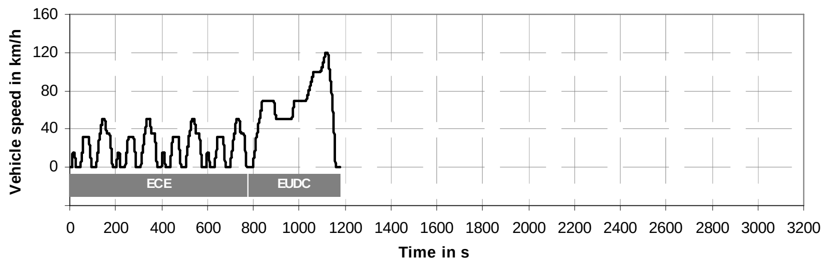

Figure 1: Official European Driving Cycle (EDC)

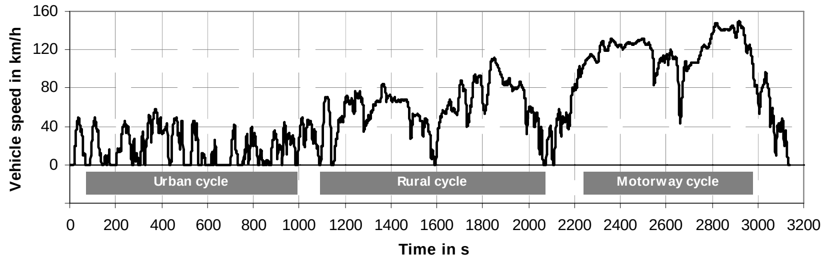

Figure 2: Real world driving cycle Artemis (CADC)

The measurements were performed on a chassis dynamometer (Fig. 3) in accordance with the current European Exhaust Emissions Regulation 70/220/EEC [3]. The emissions of carbon monoxide (CO), total hydrocarbons (T.HC), nitrogen oxides (NOx) and carbon dioxide (CO_2) were measured in accordance with this Regulation. Furthermore, emissions of methane (CH_4) and nitrogen monoxide (NO) were measured to determine the emissions of non-methane hydrocarbons (NMHC) and nitrogen dioxide (NO_2).

In addition to the gaseous emissions, the particulate mass (PMm) and particulate number (PMc) were measured. The facility is equipped with a dual full-flow dilution tunnel: one tunnel for testing diesel vehicles, the other for otto cycled vehicles (gasoline and gas vehicles). This arrangement excludes interference due to different exhaust gas compositions and temperatures. The exhaust gas flows from the tailpipe to the tunnel through a heated/insulated (T>353K) corrugated, stainless steel tube having a length of about 5.5 m and diameter of about 8 cm. The flow rate in the constant volume sampling (CVS) tunnel was set in accordance with the European Regulation.

Special care was taken in setting the appropriate flow rate in the CVS tunnel during the CNG vehicle measurements in order to avoid water condensation. The probes for the particle number and mass sampling were installed more than 4 m, i.e. more than 10 tunnel diameters, downstream of the mixing point, to ensure complete mixing of dilution air with the exhaust gas.

The measurement of PMm was done according to the European specifications with two successive Teflon-coated glass-fiber filters. The filters were conditioned before and after the sampling for at least 2 h to achieve equilibrium. A microbalance with a resolution of 0.1 µg was used for weighing the glass-fiber filters.

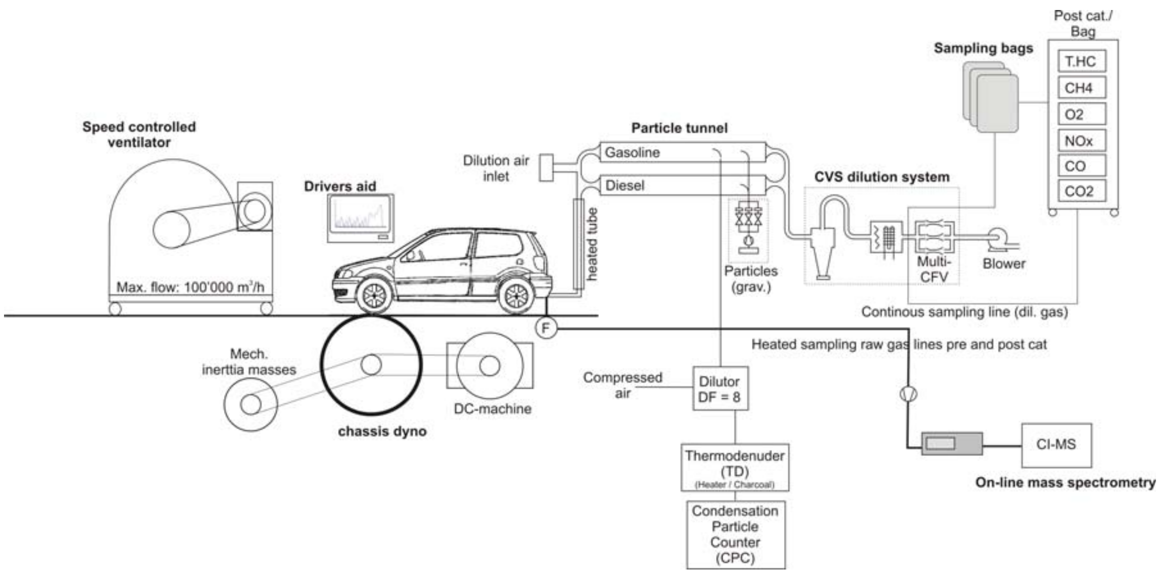

Figure 3: Experimental setup

3 Results

3.1 Greenhouse gas emissions

The measurements show that the emission levels of all powertrain technologies decreased following the introduction of more stringent exhaust emission standards. Because of the different vehicle model set, the greenhouse gas emissions were not compared based on the actual measurements but on the well-to-wheel analysis of future automotive fuels and powertrains in the European context [4].

The lowest amount of greenhouse gases are emitted by natural gas vehicles (NGV) with 21 % lower emissions compared with gasoline vehicles and 11 % lower than diesel vehicles due to the lower carbon content in the fuel. The greenhouse gases include the carbon dioxide (CO_2) as well as the methane emissions (CH_4) according their warming potential compared to CO_2.

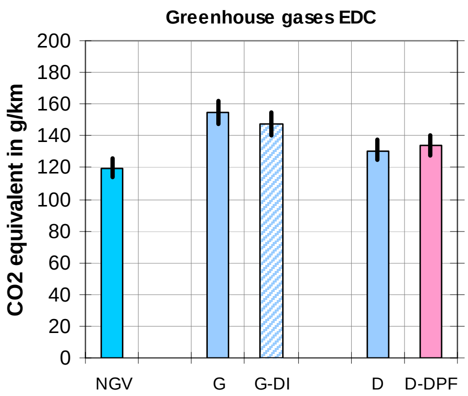

Figure 4: Measured greenhouse gas emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle (EDC) with 5% error bars

3.2 Particulate emissions

The combustion-based particles pose a serious health risk due to their very small size. The statutory determination method is the gravimetric measurement of particle mass emissions (PMm). In the opinion of experts, the health effect risks of particles are more accurately expressed by the number of particles (PMc).

The spread of particle emissions is the widest among the DPF equipped diesel vehicles. Following the discussion in [5] the performance of a DPF depends on its particle load; a new or “clean” filter has lower filtration performance in comparison to a loaded filter, where particles have accumulated to a soot cake. In response to these varying filter deposit load and the associated varying of the filtering abilities, [6] proposed that the average emission from diesel passenger cars equipped with a DPF should be evaluated using weighted values from tests with loaded and freshly regenerated DPFs. Of course, the setting of appropriate weighting factors open up a new controversy since they should be chosen according to the regeneration frequency, which in turn is a function of driving conditions.

In the present study, diesel vehicles without particle filter emit about 250 times more particles than the natural gas vehicles or the filter equipped diesel vehicles and about 50-150 times more particles than the conventional gasoline vehicles (Fig. 5). The particle number emissions of natural gas and diesel vehicles with particle filters are at a similar level and clearly below the discussed particle number limit of 5.0E+11 particles per kilometer. The mean value of the particle number emission of the conventional gasoline vehicle sample is slightly beyond the discussed limit and about three times higher than that of the natural gas sample. The gasoline vehicles with direct injection have twice as much particulate number emissions compared with conventional gasoline vehicles in the European driving cycle.

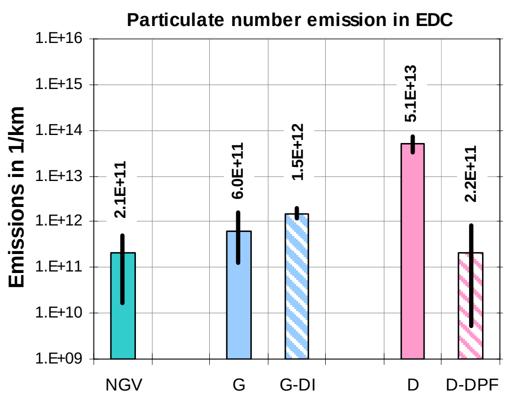

Figure 5: Measured particulate number emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle with min/max error bars

Fig. 6 shows the average particle number emission in the first part of the Artemis cycle (CADC urban). The CNG vehicles have the lowest emissions regarding particle numbers. Diesel powered vehicles with DPF have almost twice as high particulate number emissions. All tests were performed with loaded particulate filters. In tests where a sudden decrease in back pressure has been detected, a regeneration has been assumed to take place. Thus, these tests have not been further taken into account.

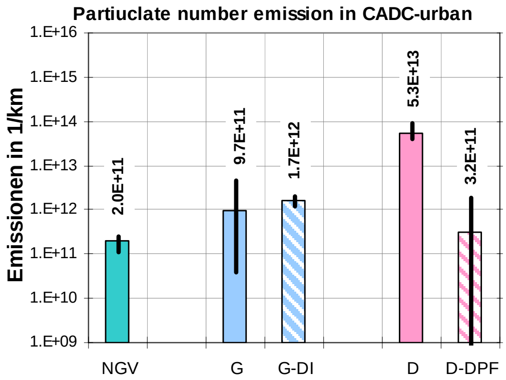

Figure 6: Measured particulate number emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis urban cycle

The test results in the rural part of the CADC cycle (Fig. 7) show similar findings. The emissions of the CNG vehicles have increased disproportionately in relation to the other technologies, while still being very low. Diesel cars without particle filters showed the exact opposite behavior: their emissions decreased in comparison with their emission performance in the urban part of the CADC driving cycle.

Beside the diesel vehicle sample with particulate filters (D-DPF), the conventional gasoline vehicles with manifold fuel injection (G) show a large dispersion in particle number emissions. While some of these vehicles emit very low particle numbers, some others emit two orders of magnitude higher particle number emissions.

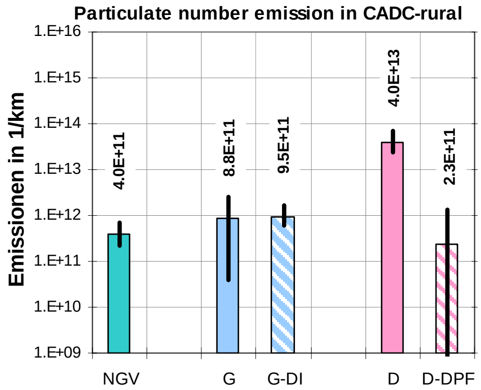

Figure 7: Measured particulate number emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate (D-DPF) filter in the Artemis rural cycle

3.3 Nitrogen oxides

The NOx emissions of gasoline and natural gas vehicles are similar and at a very low level in the European driving cycle (Fig. 8). The diesel vehicles emit about 10 times more NOx emissions.

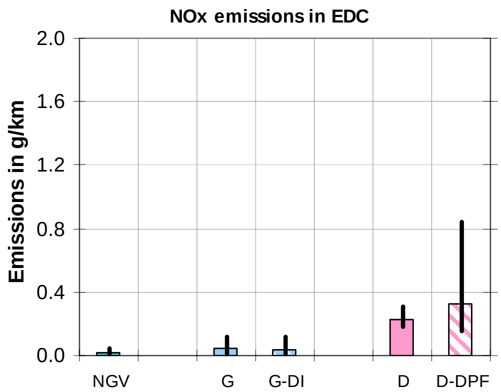

Figure 8: Measured NOx emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle

Figure 8 indicates that not all diesel vehicles comply with the actual Euro-4 NOx limit of 0.25 g/km. Only four out of six tested diesel vehicles with a particulate filter and five out of seven tested diesel vehicles without a particulate filter fall below the NOx limit. The NOx emissions in the Artemis urban, rural and motorway cycle are similar in trend to those in the European driving cycle, but at a higher level (Fig. 9 to Fig. 10).

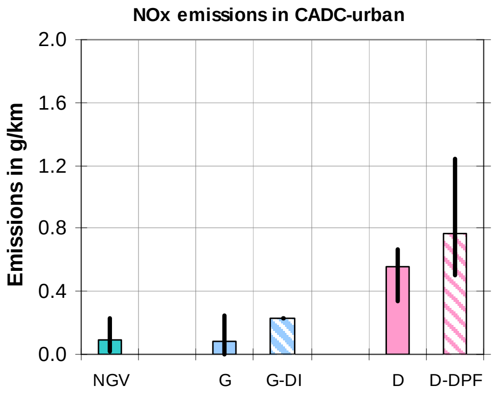

Figure 9: Measured NOx emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis urban cycle

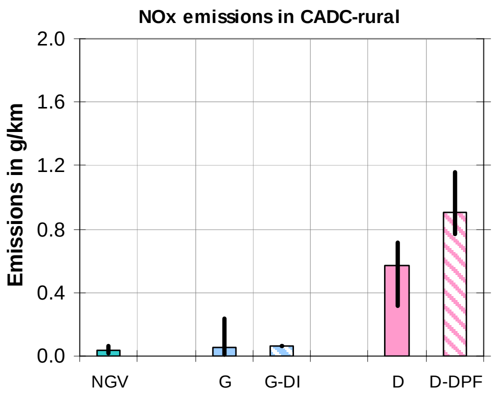

Figure 10: Measured NOx emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis rural cycle

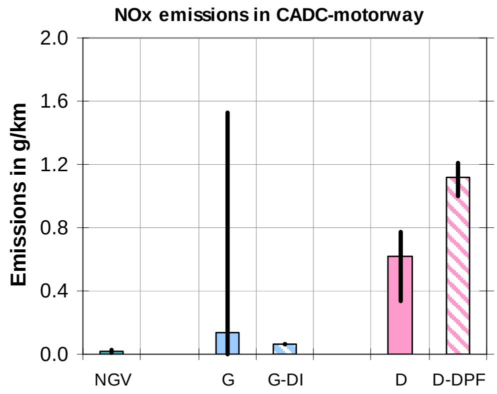

Figure 11: Measured NOx emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis motorway cycle

One of the gasoline vehicles showed very high NOx emissions only in the Artemis motorway cycle. It is expected, that the engine control system of this vehicle is not optimized at high load driving regarding NOx emissions.

Within the NOx emissions, the NO_2 emissions are more important than the NO emissions due to its local ozone-forming potential and its toxicity to humans. Regarding NO_2 emissions, the differences between otto and diesel cycled vehicles are even more pronounced. While gasoline and natural gas vehicles virtually emit no NO_2 in all the tested cycles, the proportion of NO_2 within NOx of the diesel vehicles is between 30–50 % (Fig. 12 - 15).

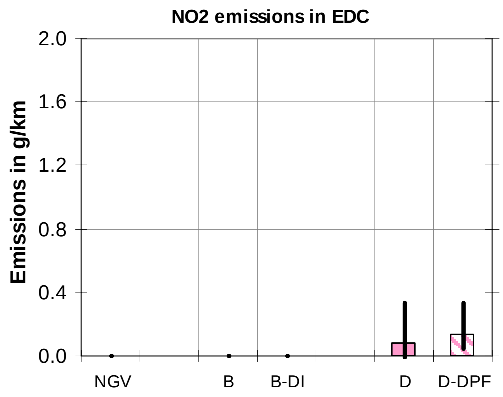

Figure 12: Measured NO2 emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle

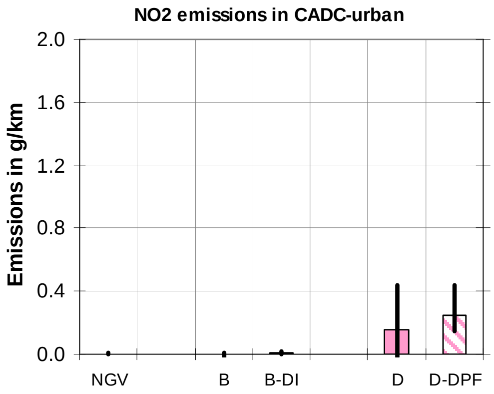

Figure 13: Measured NO2 emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis urban cycle

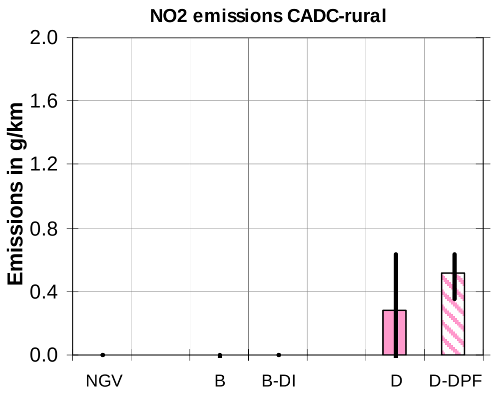

Figure 14: Measured NO2 emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis rural cycle

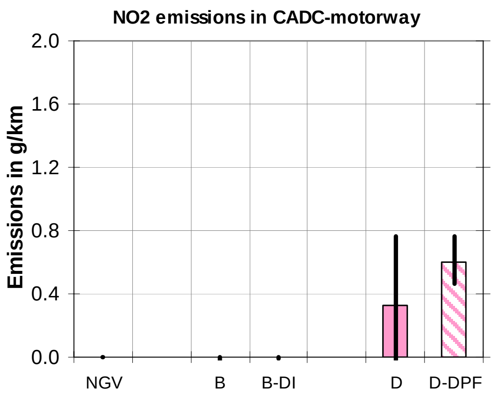

Figure 15: Measured NO2 emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis motorway cycle

3.4 Hydrocarbon emissions

Hydrocarbon emissions are the other precursor class for ozone-forming. The total hydrocarbon emissions (T.HC) of the natural gas vehicle sample are 30% higher than those of the gasoline vehicle sample and about twice as high as those of diesel vehicles with particle filter (Fig 16).

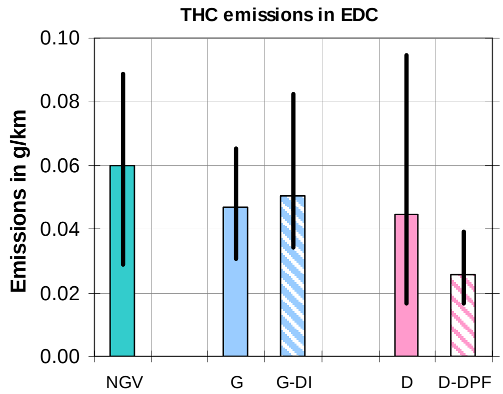

Figure 16: Measured T.HC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle

The total hydrocarbon emissions of natural gas vehicle sample consist only to 15% of non-methane hydrocarbons (NMHC) but to 85% of methane (CH_4), which is not toxic and not relevant to ozone-forming processes. But methane emissions have a predominant greenhouse gas potential which is taken into account in the greenhouse gas balance (see 3.1). The ozone-relevant NMHC emissions are lowest for natural gas vehicles (Fig. 17).

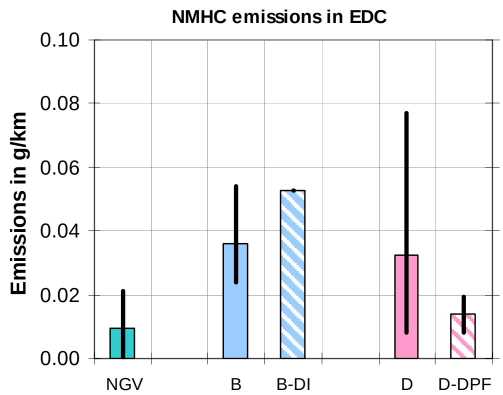

Figure 17: Measured NMHC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the European driving cycle

The T.HC and NMHC emissions in the urban part of the real-world driving cycle the CADC also shows a significant difference between otto and diesel cycled vehicles (Fig. 18 and Fig. 19):

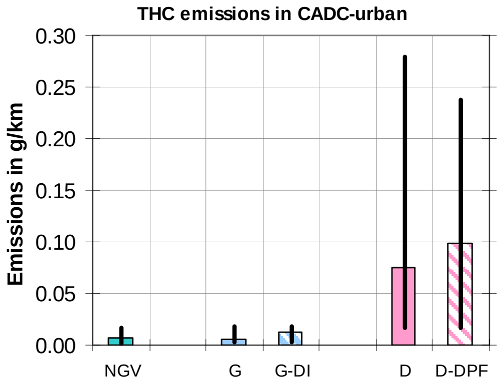

Figure 18: Measured T.HC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis urban cycle

The mean values and the range of dispersion of the T.HC emissions of the diesel vehicles are about 10 times higher than those of the otto cycled vehicles. The otto cycled vehicles show very low T.HC and virtually no NMHC emissions in the Artemis urban cycle (Fig. 18 + Fig. 19).

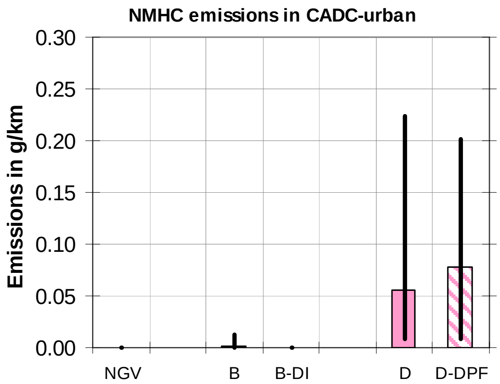

Figure 19: Measured NMHC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis urban cycle

In T.HC emissions in the Artemis rural cycle are similar to those in the European driving cycle for the otto cycled vehicles, but much lower for diesel vehicles (Fig. 20).

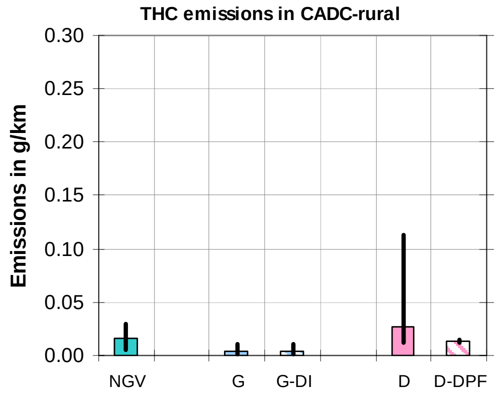

Figure 20: Measured T.HC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis rural cycle

The NMHC emissions of otto cycled vehicles are also very low in the rural part of the Artemis cycle. Those of diesel vehicles are also much lower than in the European driving cycle.

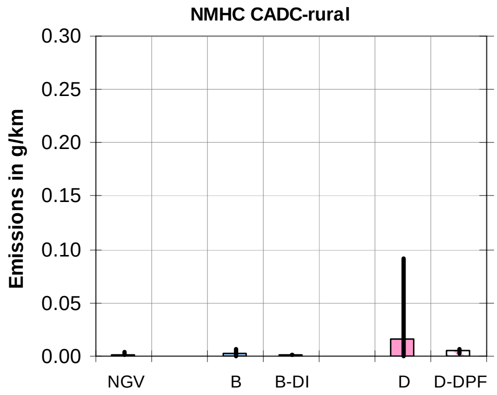

Figure 21: Measured NMHC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis rural cycle

The mean value and the range of dispersion for the T.HC emissions of the natural gas vehicles in the Artemis motorway cycle are significantly higher than in all other cycles (Fig. 22). Two of the three natural gas vehicles show air/fuel enrichment phases in this cycle, which has a large impact on the T.HC emissions (Fig. 22 + Fig. 23).

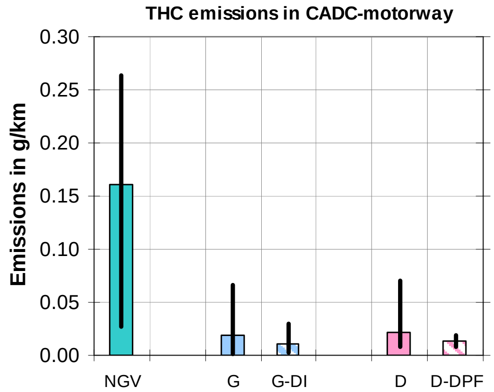

Figure 22: Measured T.HC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis motorway cycle

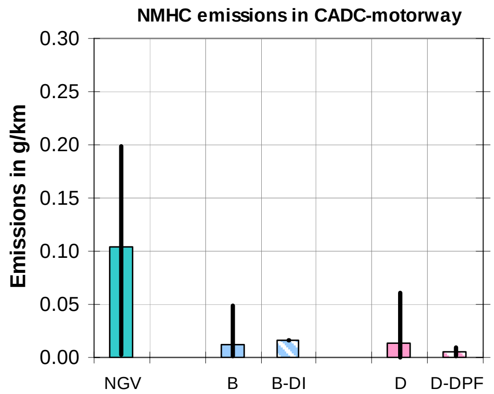

Figure 23: Measured NMHC emissions of natural gas vehicles (NGV), conventional gasoline vehicles (G), direct injected gasoline vehicles (G-DI), diesel vehicles (D) and diesel vehicles with particulate filter (D-DPF) in the Artemis motorway cycle

The increase in T.HC emissions in the mean value of the natural gas vehicle sample also reflects in their increased NMHC emissions. The gasoline and diesel vehicle samples show a similar NMHC emissions level than in the rural part of the Artemis driving cycle (CADC).

4 Conclusions

The measurements show that the emission levels of all powertrain technologies decreased substantially in recent years. Greenhouse gas emissions are increasingly significant for cleaner cars.

Due to the lower carbon content of natural gas, the greenhouse gases emitted by natural gas vehicles employed in this comparison are lowest: about 20% lower than those of gasoline and about 10% lower than those of diesel vehicles.

The main traffic-based local air quality problems in cities are particulate and ozone precursor emissions. With regard to damage potential, the particulate number is more relevant than the officially measured particle mass. Here, diesel cars without particulate filters remain the most pressing problem whereas all other cars show results at much lower levels. Concerning the local formation of ozone, NO_2 and NMHC are more relevant than the statutory limited NOx and T.HC emissions. Whereas gasoline and natural gas cars indicate a rather clean performance, the findings on diesel cars show increased emissions by one order of magnitude and much higher NO_2 contributions to NOx of about 30-50 %.

In the real-world Artemis urban driving cycle, our measurements suggest that the natural gas cars show the best results under urban driving conditions.

5 Acknowledgments

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6 References

[1] European Environment Agency, Air Pollution in Europe 1990-2004, EEA-Report 2/2007

[2] André M., The ARTEMIS European driving cycles for measuring car pollutant emissions; Science of the total Environment 334-335, 73-84 (2004)

[3] Council Directive 70/220/EEC of 20 March 1970 on the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles

[4] Concawe, EUCar, JRC; Well-to-Wheels analysis of future automotive fuels and powertrains in the European context (2006)

[5] Mohr M, Forss A-M, Lehmann U. Particle Emissions from Diesel Passenger Cars Equipped with a Particle Trap in Comparison to other Technologies, Environmental Science and Technology 40, 2375-2383, 2006

[6] Mohr M, Lehmann U, Margaria G. ACEA program on the emissions of fine particulates from passenger cars, Part 1: Particulate characterization of a wide range of engine technologies. SAE Paper 2003-01-1889, 2003

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