Particle Characterisation of Modern CNG, Gasoline and Diesel Passenger Cars

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ABSTRACT

Tailpipe particle measurements have been performed in Euro-4 passenger cars. The investigation included compressed natural gas fuelled (bifuel vehicle concepts, commercially available) spark-ignition vehicles, gasoline port-injection spark-ignition vehicles, gasoline direct injection spark-ignition vehicles as well as compression ignited, diesel vehicles with and without particle filters. Particle number and soot mass was measured. In addition particle number size distributions have been recorded at constant vehicle speed operation.

In the current study, the particle emissions of Compressed Natural Gas (CNG) vehicles are significantly lower than the corresponding ones of the other spark-ignition vehicles. While direct injection spark-ignition vehicles exhibited high particle emission, only topped by the diesel vehicles without a particle filter, diesel vehicles with particle filters had lowest particulate emission, provided the diesel particulate filter was not regenerated shortly prior to the measurement cycle. CNG vehicles had almost as low particulate emissions in all cycle parts with low and moderate vehicle speeds. At typical highway driving speeds CNG vehicle particle emissions were significantly higher than the corresponding ones of the diesel particulate filter equipped vehicles. The enrichment of fuel-air mixture was identified as the main reason for the particle emission of the CNG vehicles at high vehicle speeds. We believe this enrichment to be a remnant from the gasoline operation the engine was originally designed for. In gasoline engines enrichment of the mixture reduces process and exhaust gas temperatures mainly due to fuel evaporation during and following the intake, protecting the catalyst from high temperatures. In parallel it improves engine performance and torque due to increased flame velocity. Since CNG-rich mixtures only slightly reduce process or exhaust temperatures and the maximal flame speed is at nearly stoichiometric air-fuel ratios we identify there a relatively easy to capture potential which, if reaped, may lead to the cleanest possible vehicle propulsion system.

INTRODUCTION

A significant reduction of CO₂ emissions in the mobility sector is a major challenge for the next decades. In combination with efficient powertrain technologies, the potential of natural gas is excellent for a comparably high as well as cost effective reduction in CO₂ and toxic emissions in the near future.

In the recent past our laboratory in collaboration with the Federal Institute of Technology of Zurich (ETHZ) has demonstrated the potential of a natural-gas optimised engine vehicle with the Clean Engine Vehicle (CEV) project. The vehicle used was a production line small sedan (model year 2000) with a curb weight of 1020kg. The achieved goal was 30% lower CO₂ emissions than the gasoline vehicle while staying in compliance with Euro-4 as well as SULEV emission limits [1]. Also recently major passenger car manufacturers have modified gasoline fuelled spark-ignition engines for bifuel operation with CNG and gasoline. As a result, some bifuel CNG-gasoline vehicles have been introduced on the European market. While the bifuel concept is an important feature for customers, given the scarcity of CNG refuelling stations, it inhibits the exploiting of the full potential of CNG powertrains. In parallel, the relative low numbers of CNG vehicles on the road still constrains the resources dedicated by automotive industries to their development. CNG vehicles have to use established parts as well as concepts from their pure gasoline counterpart models. A main issue concerns the emissions from such vehicles. Certainly, they comply with the recent legislation limits, but are they better or worse than their peers? We are not aware of any systematic recent studies and comparisons.

In this paper we examine the particle emissions of typical Euro IV propulsion systems for passenger cars. Typically particles are measured with gravimetric methods. The newest vehicle technologies, though, result in emissions often in the resolution domain of gravimetric methods. We used the gravimetric as well as the particle counting method in order to achieve comprehensive re-
The counted particles from internal combustion engines are usually divided into solid and volatile particles. The solid particles mainly consist of agglomerated carbonaceous primary particles, which are in general referred to as soot. The volatile nanoparticles are usually formed by nucleation of sulfuric acid, water, and other species. These two different kinds of particles form clearly distinguishable modes in the number size distributions, designated as “accumulation” and as “nucleation mode” [2]. Extensive comparison of different powertrain technologies was carried out by [3], though no CNG systems had been included. Further investigations moved in the direction of emission modeling and inventory building [4] or assessing cold start influence on diesel and/or gasoline passenger car engines [2, 5]. Again no comparisons concerning CNG system were reported there.

In the present paper we aim to address the questions of particle emission from current market-available CNG vehicles and compare them to other current technologies. The comparison extends only to EURO-IV vehicles including modern direct injected (DI) gasoline powered vehicles as well as conventional multi-point intake manifold injected (MPI) gasoline vehicles. As comparable peers from the diesel side, we chose a series of vehicles equipped with, as well as without, a particulate filter.

**EXPERIMENTAL SETUP**

**VEHICLES**

All vehicles examined in this study have been certified according to Euro-IV regulations. They are serial production vehicles and have been borrowed for the measurements from their normal owners and drivers. All vehicles were newer than 7 years and had less than 100'000 km. All vehicles have been thoroughly checked prior to the measurements for possible technical defects.

All experiments were conducted with commercial fuels (sulphur content of less than 10 ppm) with the installed lubricating oil filter and commercial lubricating oil. The tests using the New European Driving Cycle (Fig. 1) were started after vehicle conditioning at 23 °C with cold engines. The other tests using the real-world Common Artemis Driving Cycle (Fig. 2) were started with warmed up engines. The lubricating oil temperature was increased to a minimum 90°C by conditioning the vehicle on the chassis dynamometer prior to the test.

The investigations extended to 3 bifuel market available passenger cars powered by CNG from major European manufacturers. Their displacement ranged from 1.6 to 2.0 lt. All engines had stoichiometric burning lay-out and were modified gasoline engines. The gasoline vehicle fleet comprised of 19 passenger cars, 16 with MPI and 3 with DI engine technology. Included were vehicles of European and Japanese manufacturers. The engine displacement of the MPI cars ranged from 1.2 to 3.9 lt, while for the DI cars from 1.6 to 4.5 lt. In addition, the tests included 12 diesel passenger cars of European and Japanese origin; 6 out of these vehicles had an OEM fitted diesel particulate filter (DPF). The engines’ displacements ranged from 1.2 to 2.2 lt for the diesels without a DPF and from 1.2 to 3.7 lt for the DPF equipped diesel vehicles.

**DRIVING CYCLES**

The reported results are mainly based on measurements during the New European Driving Cycle (NEDC), used for type approval purposes, Fig. 1, and the real-world Common Artemis Driving Cycle (CADC), Fig. 2. The NEDC consists of an urban part, the ECE (duration: 780 s, maximum speed: 50 km/h), and an extra-urban part, the EUDC (duration 400 s, maximum speed: 120 km/h). The CADC is composed of an urban (duration 920 s,
maximum speed: 58 km/h), an extra urban road (duration 980 s, maximum speed: 112 km/h), and a highway part (duration 735 s, maximum speed: 150 km/h). Speed-time cycles as used in the present study favour in emission questions vehicles with a higher power-to-weight ratio, since the latter avoid the higher load parts during these tests. In particular, spark-ignition engines use rich mixtures at higher loads, severely deteriorating their emission behaviour.

Besides the NEDC and CADC, constant speed driving tests were performed in order to assess particle number size distribution. For deeper insights, the interested reader is referred to [2, 3 and 6].

PARTICLE MEASUREMENTS

The measurements were performed on a chassis dynamometer at the Empa laboratories. Our facility has two dual full-flow dilution tunnels: one tunnel for testing diesel vehicles, the other for gasoline vehicles. This arrangement excludes interference due to different exhaust gas compositions and exhaust gas temperatures. Transient measurements of gaseous components as well as temperatures and pressures at several points along the exhaust gas and sampling line, routinely accompanied the particle measurements. The exhaust gas flows from the tailpipe to the tunnel through a heated/insulated (T>80 °C) 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 to 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. Due to the higher hydrogen-to-carbon ratio for CNG than for either gasoline or diesel fuel, the concentration of water in the exhaust is also higher for CNG.

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 and the exhaust gas. In the appendix we provide the schematic of the experimental setup.

Particle Mass Measurement. The gravimetric measurement procedure was done according to the European specifications [7] with two successive Teflon-coated glass-fibre filters (Pallflex, T60A20, retention for DOP 0.3 μm: 96.4%). The temperature of the filter holder was thermally uncontrolled, but the aerosol sample was held below 52 °C by the dilution. Before and after the sampling, the filters were conditioned at 25±1°C and 50% relative humidity, for at least 2 h to achieve equilibrium. A microbalance (Mettler Toledo, UMX 2) with a resolution of 0.1μg was used for the weighing. A continuous measuring photoacoustic soot sensor (AVL MSS) was directly connected to the CVS tunnel for soot-mass detection with a resolution of 10 μg/m³.

Particle Number Measurement. The particle number measurement setup was based on the initial findings of the PMP expert group. PMP is an international working group under the auspices of the UNECE WP29 focusing on development of a new appropriate particle measurement for type approval purposes. The sample flow was extracted from the dilution tunnel and was diluted by a one- or two-stage ejector-pump diluter (Pallas GmbH; Dekati Ltd.) at a dilution ratio of 10 or 100, respectively [8]. Dilution should ensure that the total number concentration of non volatile particles does not exceed 10⁴ 1/cm³ in the particle counter. Subsequently, the aerosol flowed through a metal tube (length 50 cm, diameter 20 mm), heated to a temperature of 300 °C, to evaporate volatile particles formed by nucleation in the exhaust and sampling line. A condensation particle counter (TSI INC., CPC3022A) then counted the particles. This instrument has single particle detection and a 50% counting efficiency for 7nm diameter particles. More details about the CPC principles are available in Reference [9]. The total transit time, between the probe in the tunnel and the particle counter, was under 10 s. Upstream of the evaporation tube (ET), another CPC (TSI INC., CPC3022A) was connected to the sampling line to measure the number of particles including the possible volatile fraction. An important issue is the specification of the ET. This unit should have the capability to evaporate a sufficient quantity of volatile material, yet the losses of solid particles by thermophoresis and diffusion should be minimal [10]. According to the PMP draft the evaporation unit should fulfil the following two criteria: (a) a penetration of 80% or more for solid particles of 30 nm, 50 nm, and 100 nm diameter and (b) an evaporation efficiency of 99% or more of tetracant particles (C₄₀H₇₂) with a diameter of 30nm and a concentration of at least 1000 1/cm³. More details of the measurement setup and evaluation are published in [6]. A correction of the systematic errors mentioned above would require a detailed knowledge of the number size distribution throughout the test cycle, which is usually not available. Rough estimates result in total losses of less than 20% for a typical diesel exhaust aerosol.

CPC accuracy lies under ±10% while the repeatability of the achieved dilution is under ±5%. Even higher variability is introduced by the vehicle condition prior to the test. All tested vehicles have been through our preconditioning routine aiming in at least partly eliminating the associated variability. In [15] we have provided some evidence concerning the variability of repeated particle number measurements.

Particle Number Size Distribution measured by Scanning Mobility Particle Sizer (SMPS TSI Inc.). During constant driving test measurements a SMPS [11] consisting of a differential mobility analyzer (DMA, model 3071, TSI Inc.) and a condensation particle counter (CPC, model 3025, TSI Inc.), size range: 10-430 nm,
was connected in line with a second ET after the ejector-pump diluter to measure the number size distribution (NSD). This ET was equipped with a bypass in order to measure the NSD of particles including the possible volatile fraction.

**RESULTS AND DISCUSSION**

**COMPARISON OF PARTICLE NUMBER VEHICLE EMISSIONS**

![Graph showing particle number emissions for different vehicle technologies](image)

Fig. 3: Average particle number emission of the investigated powertrain technologies on the NEDC cycle (the bars extend from the maximum to the minimum observations for each technology).

**NEDC.** Fig. 3 shows the average tailpipe particle number emission per km for the investigated passenger cars measured during the NEDC cycle. As already mentioned, for each category at least three different vehicles were under scrutiny. There are two bars for each technology; one showing the average total number as measured by a CPC, the other showing only the non volatile particles as measured by the CPC downstream an evaporation tube (ET).

As expected, the measured particle emissions from diesel powered cars without a particle filter were the highest. Lower by more than one order of magnitude was the particulate emission of the gasoline direct injected vehicles. These emissions were significantly higher than the corresponding ones from conventional gasoline MPI driven cars. Particle emissions of the CNG and the diesel DPF-equipped vehicles are clearly the lowest. Several of the tested vehicles achieved even $10^{10}$/km particles. Particularly the diesel vehicles with DPF attract attention.

As can be seen by Fig. 3, the spread of particulate emissions is the widest among the DPF equipped diesel vehicles. On the one hand this is due to the different filter technologies (one particular DPF configuration was persistently located on the high end of the bar) and on the other hand due to different conditions of the accumulated filter cake. Following the discussion in [6] the performance of a DPF depends on its particulate load; a new or “clean” filter has lower filtration performance in comparison to a loaded filter, where particles have accumulated to a soot cake. This is also reflected in studies of the pressure drop across the filter as well as in simulation studies where the permeability as well as the resistance of the filter walls to the exhaust gas flow has to be continually adjusted, [12, 13 and 14] during the filter loading phase.

In response to these varying filter deposit load and the associated varying of the filtering abilities, [15] 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.

During the NEDC cycle measurements presented in this paper we proceeded having the following distinction: We averaged all particulate emissions coming from tests which have been started with a fresh regenerated filter. These are presented in Fig. 3 by the second bar group (from the right). In comparison the results from all cycles with a loaded particulate filter are depicted by the far right bars. During these cycles no regeneration was observed. No attempt was made to determine the deposit load of the filters prior or after the test. Attention was paid to start the test with a loaded filter and to assure that no regeneration took place during the cycle. Experiments where regenerations took place during the cycle have been omitted from further evaluation and not included in results presented in this paper. In accordance with the simulations and the experimental studies mentioned before, the particle emissions of diesel vehicles with a fresh regenerated filter are substantially higher (2 to 3 times more) than the ones with a loaded filter.

**CADC.** In Fig. 4 we plot the average particulate emission in the first, urban, part of the CADC cycle. Some additional insights are provided here. The CNG vehicles have the lowest emissions in terms of all particles as well as of only nonvolatile particles. Diesel powered vehicles with DPF have almost twice as high particulate emissions. We did not perform any investigations with the freshly regenerated particulate filters in the CADC cycles. We started all tests with loaded particulate filters. In those tests where we experienced a sudden decrease
of back pressure we associated a regeneration taking place. We did not account such tests for further results.

Fig. 4: Average particle number emission of the investigated powertrain technologies on the CADC urban cycle (the bars extend from the maximum to the minimum observations for each technology).

Nevertheless, the situation is more complex with the gasoline vehicles in the urban part of the CADC cycle. MPI and DI gasoline powered vehicles have similar overall particle emission. Looking though only at the nonvolatile part of the particles there is clear evidence of the higher environmental impact of the DI exhaust. Not surprisingly, diesel vehicles without a DPF have clearly the highest particle emissions.

The extra urban of the CADC cycle (Fig. 5) does not give a much different picture. The emissions of the CNG vehicles have increased disproportionately in respect to the other technologies, still though being very low. Diesels without particle filters showed the exact opposed behavior. Their emissions decreased in respect to their own emission in the urban CADC particle, still though they build the highest particulate emitting propulsion technology.

The highway part of the CADC cycle shows substantially larger overall particles for every technology, Fig. 6. The differences between the overall and the nonvolatile fraction have though increased substantially, giving evidence of increased condensate contents. Taking only the nonvolatile fraction into account we observe high particulate emissions by the CNG vehicles. These are even slightly higher than for both gasoline vehicle categories. It is interesting, that one of the tested CNG vehicles had very high particle emissions, reaching at the CPC downstream the evaporation tube, $1.02 \times 10^{13}$ /km, the second CNG vehicle had almost an order of magnitude less, $1.36 \times 10^{12}$ /km, while the third was even two orders of magnitude less, $4.37 \times 10^{10}$ /km, resulting in a high average for this category. In the time resolved emission section, further below, we will deliver a more comprehensive comparison in this issue. If taking only the two lower particle emitting CNG vehicles into account, their nonvolatile particulate emission is at the
level of the lowest MPI gasoline vehicle and by far lower than the lowest DI gasoline vehicle. Nevertheless lowest emissions, by far, in this highway part have Diesel vehicles equipped with a DPF.

COMPARISON OF PARTICLE TOTAL MASS AND SOOT MASS VEHICLE EMISSIONS

Fig. 7: Average particle total and soot mass emission of the investigated powertrain technologies on the CADC urban cycle (the bars extend from the maximum to the minimum emission for each technology).

CADC urban and extra urban. Gravimetric particle mass emissions in Figs. 7 and 8 exhibit slightly different relations among the powertrain technologies than the particle number values. The conventional diesel vehicles have up to two orders of magnitude higher emissions than the other technologies. The average of the DPF equipped Diesels is of the same order of magnitude of the averages from gasoline and CNG vehicles. Interestingly, the soot mass emission, as measured by the MSS soot sensor is substantially lower than the gravimetric results. This indicates high hydrocarbon content of the gravimetric measurements. In fact, filtered material analysis have shown that the filter contents are a mix of solid particles and absorbents. In any case, there should be kept in mind that the very low measured values corresponding to low particle burdens on the filters are strongly susceptible to background concentration variations as well as adsorption and desorption processes of gaseous compounds on the filter material. The general issue of the capability of gravimetric measurements at systems with very low particle emission was already raised by [16]. Nevertheless, the soot mass measurements resemble the tendencies of the different vehicle technologies comparably to the tendencies as given by the particle counting (Figs. 4 and 5).

Fig. 8: Average particle total and soot mass emission of the investigated powertrain technologies on the CADC extra urban cycle (the bars extend from the maximum to the minimum emission for each technology).

CADC highway. The conclusions from the first two CADC parts are similar to these from the third CADC

Fig. 9: Average particle total and soot mass emission of the investigated powertrain technologies on the CADC highway cycle (the bars extend from the maximum to the minimum emission for each technology).
highway part. The soot mass measurements performed with the MSS sensor, as shown in Fig. 9, correlate well with the non-volatile fraction of the particle number measurements (Fig. 6, bars with ET). Gravimetric measurements reveal a somehow different picture showing substantial particle emissions from the diesel DPF equipped vehicles. The high difference between the MSS sensor and the gravimetric result indicates that the gravimetric method is strongly affected by condensates and the volatile component of the emissions.

**TIME-RESOLVED PARTICLE VEHICLE EMISSIONS**

The CPCs deliver time-resolved data on emitted particle numbers. This provides insights with high sensitivity and time resolution.

Out of the various measurement series, we will limit the discussion in this paper to the four typical cases shown in Figs. 10-13. Each of these figures displays a typical CADC cycle with the time resolved signals of the two CPCs, the one measuring all particles and the other only the nonvolatile particles downstream an evaporation tube (ET). In addition, we also plot the signal of the MSS soot sensor. For being able to demonstrate possible relations of the particle emissions to the engine operation, the vehicle speed is also included in the plots.

Fig. 10: Time-resolved particle emissions of one CNG powered bifuel vehicle on the CADC cycle.

Fig. 11: Time-resolved particle emissions of the CNG powered bifuel vehicle with the highest particulate emissions during the CADC cycle.

Fig. 12: Time-resolved particle emissions of one gasoline DI powered vehicle during the CADC cycle.

Fig. 10 shows a CADC cycle of the CNG vehicle with the lowest particulate emissions, while Fig. 11 shows a typical cycle of the other CNG vehicle, the one with the highest particulate emissions at high speeds. Particulate emissions in Fig. 10 are very low throughout the whole cycle. This vehicle demonstrates the potential of a good lay-out of CNG combustion, with regard to particulate emission. The particulate emission is even lower than the emission of filter equipped diesel vehicle, Fig. 13. The volatile components are also extremely low, with only one peak during high speed driving.
A typical cycle of the CNG vehicle with high particle emissions is shown in Fig. 11. The particulate emission in the first two parts of the CADC cycle is also very low. With increasing vehicle velocity particulate emissions increase reaching very high levels over 110 km/h. This vehicle uses rich air-fuel mixture at moderate speeds (above 100 km/h) and higher loads. This was confirmed by the decline of the CO\textsubscript{2} concentration in the exhaust gas while the CO concentration increased. Typical is the situation for vehicle speeds over 130 km/h: The CO\textsubscript{2} concentration decreases from approx. 11.8 vol\% at 100 km/h to 9.2 vol\% at vehicle speeds over 130 km/h. The CO concentration on the other hand increases up to 4 vol\% at vehicle speeds over 130 km/h. It is difficult to express these speeds in terms of engine loads without knowing the exact characteristics of the engine. Nevertheless a hint is given by the vehicle top speed, which is 157 km/h for CNG operation.

We cannot imagine a reason or benefit for the enrichment of the fuel mixture in combination with the CNG fuel. We believe that the fuel enrichment may be a remnant from the gasoline operation of the engine, where it decreases process temperatures (mainly by evaporation of the liquid fuel during intake and early compression), thus protecting the catalyst and other engine parts. In addition the enrichment at high loads aims to increase the engine performance reaping the higher flame speed of rich gasoline air fuel mixtures. Since the highest flame speeds in CNG-air mixtures are reached by almost stoichiometric mixtures, [17, 18, 19, 20, 21 and 22], the fuel enrichment at high loads is not meaningful. The engine was derived from the gasoline counterpart and uses two electronic control units. The main unit is the gasoline engine control unit, responsible for main operation as well as the entire gasoline operation, and sends major signals to the gas engine control unit, which undertakes necessary changes for the gas operation. The use of an already available gasoline engine based control and the low associated costs appear to us the only reason for the fuel enrichment at high loads.

The question concerning the soot precursors in CNG combustion is beyond the scope of this paper. We assume that combustion under rich conditions has a soot potential, also because full homogenization of the mixture is not always achievable. In addition, good mixing of CNG with air is always an issue. Nevertheless, the agreement of the optoaoustic soot sensor signal with the signal of the particle counter downstream the evaporation tube provides evidence for the high soot emission at high vehicle speeds.

Fig. 12 shows the time resolved particle emission of the DI gasoline vehicle. At high vehicle speeds the pattern of the particle emission is similar to the CNG vehicles. Additional particle peaks during each stronger acceleration are evident. Overall the particle emissions are higher than the ones of the CNG vehicles confirming the picture given by Figs 4-6.

Fig. 13: Time-resolved particle emissions of one diesel DPF equipped vehicle during the CADC cycle.

Diesel vehicles with the efficient particulate filters show very weak, if any, relations among the driving conditions and the particle emissions, Fig. 13. This is an indication of the very high filtration efficiency. Only in the higher vehicle speeds we can observe some noteworthy particle emission. This could either due to “stripping” of some particulates through the DPF at higher exhaust condensation or due to post-DPF condensation.

Figs. 10-13 provide also good evidence for the correlation of the MSS soot sensor and the signal of the CPC downstream of the ET.

PARTICLE NUMBER SIZE DISTRIBUTIONS AT CONSTANT VEHICLE SPEED

The Number Size Distributions (NSD) in Fig. 14 are examples from two CNG powered vehicles at constant speed. Both NSDs indicate accumulation modes (mode at ca. 55 nm) and a nucleation mode (d\textsubscript{mode} ca. 13 nm). The vehicle denoted with CNG A corresponds to the CNG vehicle with the highest particulate emissions at high speeds, while CNG B to the CNG vehicles with the low emissions at high speeds. We performed different scans with vehicle B at 120 km/h mainly to demonstrate the composition of the particles. It is obvious that the nucleation mode is comprised by mainly volatile particles, since it almost disappears when installing an evaporation tube upstream of the CPC.
SUMMARY AND CONCLUSIONS

This study concentrated on the particle emissions of a series of Euro-4 vehicles with different propulsion technologies. Particle measurements have been performed employing the type approval gravimetric technique, particle counting and optoacoustical sensing. During most measurements volatile and non-volatile particle fractions have been monitored simultaneously. Number size distributions have been also acquired in order to identify relevant modes.

At typical urban and extra urban driving conditions CNG and diesel fuelled DPF equipped vehicles have the lowest particle number emissions. Particle number emissions of MPI gasoline vehicles are, depending on the driving cycle, at least twice as high. DI gasoline vehicles have one order of magnitude higher particulate emissions, while diesel vehicles without DPFs emit even one order of magnitude more particles.

Emission patterns change at highway driving where CNG and gasoline fuelled vehicles have comparable particle emissions, one order of magnitude higher than diesel DPF equipped vehicles. Diesel vehicles without DPF have also at highway driving the highest particulate emissions (two orders of magnitude higher than their DPF equipped counterparts). The volatile component of the particles is during highway driving substantially higher than during urban or extra urban driving.

Optoacoustical soot measurements correlate well with non-volatile particle number counting. On the other hand, gravimetric particle measurements seem to be at their detection limits.

Specific for natural gas fuelled (bifuel, commercially available) spark-ignition Euro-4 vehicles we have identified:

- Particles emissions lower than diesel fuelled DPF equipped passenger cars at low speed driving conditions (CADC urban phase).
- Particle emissions in the order of magnitude of the diesel fuelled DPF vehicles, provided the DPF was loaded and not freshly regenerated at extra urban road conditions (CADC extra urban phase).
- Disproportionately higher particle emissions similar to gasoline DI passenger cars at typical highway conditions (CADC highway phase).
The particle emissions at high speed conditions of the CNG vehicles consist of an accumulation mode, mostly consistent of soot, and a nucleation mode consisting of volatile aerosols. Similar structure have the particles emitted by the DI gasoline cars.

We identified as a main reason for the high particle emission of the CNG vehicles at high vehicle speeds the enrichment of the fuel-air mixture at higher loads. This enrichment, we believe, is a remnant from the gasoline operation, the engines had been originally designed for. Rich CNG-air mixtures do not have the advantages of rich gasoline-air mixtures. Therefore a CNG-targeted combustion management lay-out can reduce the particle emission to levels significantly lower than diesel DPF equipped vehicles. Only one out of the three tested CNG vehicles had the appropriate lay-out and achieved this goal.

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CONTACT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

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<th>Abbreviations</th>
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<td>CADC</td>
<td>Common Artemis Driving Cycle</td>
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<td>CNG</td>
<td>Compressed Natural Gas</td>
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<td>CPC</td>
<td>Condensation Particle Counter</td>
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<td>CVS</td>
<td>Constant Volume Sampling Tunnel</td>
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<td>DI</td>
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<td>DPF</td>
<td>Diesel Particulate Filter</td>
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<td>ET</td>
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<td>NEDC</td>
<td>New European Driving Cycle</td>
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<td>NSD</td>
<td>Number Size Distribution</td>
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<td>MPI</td>
<td>Multi-point intake manifold injected gasoline engine</td>
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<td>MSS</td>
<td>Micro Soot Sensor=Photoacoustic soot sensor</td>
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<td>TWC</td>
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APPENDIX

Schematic of the measurement setup