On-road particle number measurements using a portable emission measurement system (PEMS)

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HIGHLIGHTS
• Correlation of a PN PEMS with a test cell PMP set-up, and real-world driving.
• Measured PN-to-soot ratio suggests PN PEMS is capable of on-road measurements.
• Impact of different driving styles on PN emissions.
• PN on-road measurements at different ambient temperatures with and without cold start phase.

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ABSTRACT
In this study the on-road particle number (PN) performance of a Euro-5 direct-injection (DI) gasoline passenger car was investigated. PN emissions were measured using the prototype of a portable emission measurement system (PEMS).

PN PEMS correlations with chassis dynamometer tests show a good agreement with a chassis dynamometer set-up down to emissions in the range of $1 \times 10^{10}$ #/km. Parallel on-line soot measurements by a photo acoustic soot sensor (PASS) were applied as independent measurement technique and indicate a good on-road performance for the PN-PEMS. PN-to-soot ratios were $1.3 \times 10^{12}$ #/mg, which was comparable for both test cell and on-road measurements.

During on-road trips different driving styles as well as different road types were investigated. Comparisons to the world harmonized light-duty test cycle (WLTC) 5.3 and to European field operational test (euroFOT) data indicate the PEMS trips to be representative for normal driving. Driving situations in varying traffic seem to be a major contributor to a high test-to-test variability of PN emissions. However, there is a trend to increasing PN emissions with more severe driving styles. A cold start effect is clearly visible for PN, especially at low ambient temperatures down to 8°C.

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1. Introduction

In 2011 the European Union (EU) introduced a solid particle number (PN) emission limit of $6 \times 10^{11}$ #/km for Diesel vehicles. Tests are conducted over the new European driving cycle (NEDC) and according to the Particle Measurement Protocol (PMP). With the first stage of the new Euro-6 regulation (Euro-6b) launched in September 2014, a PN limit of $6 \times 10^{12}$ #/km is also imposed on direct injection (DI) gasoline vehicles (EU, 2011) and will be lowered to $6 \times 10^{11}$ #/km in 2017 as already mandatory for Diesel vehicles. For Euro-6c, scheduled for 2017, the EU Commission works on the development and implementation of ‘Real Driving Emissions’ that is supposed to include the regulation of Diesel NOx and possibly PN at a later stage. On-road PN emissions are currently subject of research. In this regard, it appears as if the portable emission measurement system (PEMS) is a viable method.

In this study a pre-series mobile device measured fine particles...
<300 nm, which are considered to be the main contributor to total PN. Similar to the method prescribed by the European legislation, the PN PEMS applies a hot dilution cascade (three steps: 10, 100, 300) and an evaporation tube (ET) for the conditioning of the aerosol. The aerosol is charged by a corona charger and the particles are detected by the induced current at two stages (diffusion and filter stage) (Matter, 2013).

Several correlation measurements of the PN PEMS with an established regulatory test cell equipment are presented in this paper. On-road performance was investigated by comparison with an independent measurement technique (photo acoustic soot sensor (PASS)). In addition, on-road tests with a Euro-5 gasoline passenger vehicle are presented under different environmental and driving conditions.

2. Instrumentation

The investigated PN PEMS is the pre-series instrument Nano-met3-PS manufactured by Matter Aerosol AG (Testo company, Switzerland). It was designed to be comparable to the current PMP regulation (R-83) regarding the PN measurement on chassis dynamometers in terms of particle conditioning and detection parameters.

Fig. 1 shows a schematic view of the device in comparison to a test cell PMP system. The main characteristics of both instruments are compared in Table 1.

The PN PEMS samples raw exhaust directly from the tailpipe while the PMP system collects to some extent aged particles out of a constant volume sampler (CVS) (Fig. 1). Hence a different shape of particle peaks is expected for the PN PEMS compared to the PMP results. The total number calculated as the integral over each particle peak, however, is supposed to be in the same range, not taking into account coagulation and thermophoretic losses.

PN PEMS sample conditioning takes place in a volatile particle remover (VPR) consisting of a hot diluter and an evaporation tube (ET), comparable to the PMP R-83 procedure. The sample passes a hot dilution in a rotating disk diluter at 150 °C with dilution factors of 10, 100 or 300 and is heated to 300 °C in the ET. In the subsequent cooling down zone according to the manufacturer no recondensation occurs because the dilution factor has been set to a high enough value so that the sample does not pass its dew point (Matter, 2013).

Particle detection in the PN PEMS is based on corona charging of the aerosol particles. In the particle detector the aerosol is charged by a unipolar corona diffusion charger and the resulting current is measured in two stages. The charged aerosol passes a diffusion stage where particles are deposited by diffusion processes while the remaining particles are collected in the filter stage. The electrical current is measured in both stages using two sensitive electrometers. Based on the ratio of both electrometer signals, the mean particle size can be estimated, however, this is not subject of the present study.

The PN PEMS makes use of diffusion charging which is a completely different particle measurement principle compared to condensation particle counters (CPC) of PMP systems (Table 1). CPCs have a 50% counting efficiency at 23 nm that increases to 100% for particles larger than 100 nm. On the other hand, diffusion chargers show an exponential size dependent efficiency curve (Fierz et al., 2008) because larger particles can carry more charges that lead to higher currents (Giechaskiel et al., 2014a). The PN PEMS in this study is factory calibrated using monodisperse soot particles at 80 nm (Matter, 2013). As the efficiency curve is not linearly correlated with the particle size (exponent of 1.1 according to Fierz et al., 2011 for this detector), there is a well-known deviation for particles larger or smaller than 80 nm.

3. Chassis dynamometer tests

The performance of the PN PEMS was investigated by correlation of experimental data with results obtained with established regulatory test cell equipment. The preconditioning stage consisting of a hot diluter and an evaporation tube from the PN PEMS is similar to the PMP equipment, however, the measurement position as well as the detector principle are different (see chapter 2).

The chassis dynamometer tests were conducted at the Ford Research Center in Aachen. The test cell is equipped with the Horiba MEXA-2000SPCS which is compliant to R-83. All PN measurements were performed according to the current legislative procedures for type approval (EU, 2011). Several driving cycles such as NEDC, world harmonized light-duty test cycle (WLTC) 5.3 and other laboratory cycles representing on-road driving were conducted with different test vehicles (Diesel and gasoline operated) producing PN emissions varying over several orders of magnitude.

Second-by-second PN (in #/s) was obtained by multiplying the
PN concentration provided by the PN PEMS with the exhaust volume which was measured at the CVS tunnel. The result is very sensitive to the time alignment between concentration and exhaust volume, a few seconds offset can cause up to 50% PN difference over the complete test cycle. The PN PEMS concentration has a different time basis compared to the PN counts and the exhaust volume provided by the test cell. Therefore, the PN PEMS concentration trace was shifted in steps of 1 s relative to the exhaust flow of the test cell. In each step the PN-PEMS result in #/s was calculated by multiplying PN concentration with the exhaust volume and the mean quadratic deviation from the PMP PN counts was calculated. The best time alignment between PN PEMS and test cell equipment was then given by the lowest deviation value. This least square method does not determine the best correlation between peaks of concentration and exhaust volume because the exhaust volume is sensitive to the time alignment between concentration and exhaust flow. In double-logarithmic scale (upper plot in Fig. 3), PMP data points in the region <10^{10} #/km deviate significantly from the 1:1 PN PEMS correlation line. Thus, a limit of detection of the PN PEMS around 1·10^{10} #/km is inferred, which is more than one order of magnitude below the current NEDC Diesel PN emission limit.

The linear scale diagram in Fig. 3 (lower plot) shows a good linear correlation of the data points with a coefficient of determination R^2 of 0.92. In this calculation all data <10^{10} #/km were not considered as they are below the detection limit of the PN PEMS. The slope of the regression line is 1.21 ± 0.26 (95% confidence interval) and indicates that the PN PEMS generally records around 20% higher particle counts than the test cell equipment. This deviation probably results from coagulation effects and differences between the detection principles. The PN PEMS is factory calibrated with a PMP device using an 80 nm standard aerosol (see Table 1), however, more dynamic test cycles may lead to larger coagulation effects inside the transfer hose from the tailpipe to the CVS entrance and also inside the CVS tunnel. Additionally, particles with sizes differing from 80 nm lead to further deviations between the PMP system and the PN-PEMS due to the different detection principles. These results are again in-line with the before mentioned study conducted by the JRC which reports differences of −30% to 20% between both instruments (Giechaskiel et al., 2014b).

Smaller particles with diameters between 10 and 23 nm that are detected by the PN PEMS but not by the PMP set-up, can only account for a small fraction of the presently observed difference. A typical unimodal particle size distribution for a gasoline vehicle under real-world conditions has a geometric mean diameter of 45–60 nm (Khalek et al., 2010; Li et al., 2013; Maricq et al., 1999). Assuming a 50% detection efficiency at 10 nm and 23 nm for the PN PEMS and the PMP equipment, respectively, the particle number difference between both systems theoretically accounts for 5–11%.

### 3.2. Soot mass measurements

In order to assess the performance of the PN PEMS system outside the laboratory on a public road, a portable reference method is required, which can be mounted inside the vehicle in addition to the PN PEMS. Photo acoustic soot sensing is an established method for investigating the amount of soot mass present in vehicle exhaust. Soot measurements were conducted with an AVL M.O.V.E PM PEMS using a Photo Acoustic Soot Sensor (PASS) in parallel with the PN PEMS. Both detection systems were connected to the tailpipe of the vehicle.
Three laboratory tests representing on-road driving were conducted with this set-up. One example of the PN and soot time traces is shown in Fig. 4. The time alignment of the data sets was performed using a discrete cross-correlation method. This mathematical operation calculates the sum of the product of PN and soot signal for every possible offset between each other. The offset showing the largest cross correlation value represents the best time alignment between both signals.

Qualitatively, there is a good temporal correlation between PN count and soot mass resulting in a PN-to-soot ratio of $1.5 \times 10^{12} \#/mg$. Three test cycles combined yield a ratio of $1.3 \times 10^{12} \pm 2.8 \times 10^{10} \#/mg$. This result is in good agreement with previous studies. Kirchner et al. (2010) found a PN-to-soot ratio of $1.8 \times 10^{12} \#/mg$ for a DPF Diesel vehicle, Maricq et al. (2011) report a ratio of $2 \times 10^{12} \#/mg$ for a gasoline direct injection vehicle and Khalek et al. (2010) observed a correlation of $3 \times 10^{12}$ to $4 \times 10^{12} \#/mg$. Giechaskiel et al. (2012) collected data from about 50 light duty vehicles and found most PN-to-soot ratios between $1 \times 10^{12}$ and $6 \times 10^{12} \#/mg$. The temporal correlation as well as a plausible correlation factor reported in this work suggest that the PM PEMS system is a useful reference instrument for on-road measurements.

4. On-road measurements

4.1. PEMS set-up

All on-road measurements were conducted using a gasoline operated Euro-5 passenger vehicle with 2.0l displacement (149 kW) and 6-gear automatic transmission. The PN PEMS was mounted inside the trunk of the car and was connected close to the tailpipe to an exhaust flow meter (EFM) from Sensors Inc., which was controlled by a Semtech-DS Gas PEMS (see Fig. 5). The sample line was heated to a temperature of 190 °C in order to avoid condensation processes. Lead acid batteries inside the car supplied power for the instruments. Additional sensors mounted to the roof of the car were used to record ambient conditions, i.e. temperature and relative humidity. The PM PEMS was fixed on the backseat and was also connected to the EFM. The entire measurement equipment resulted in a total extra weight of roughly 200 kg.

In order to calculate PN in#/s, the PN concentration has to be multiplied with the exhaust flow measured by the EFM. Similar to the dynamometer tests, the result is very sensitive to offsets between these two signals because of different time bases. The time
Fig. 3. Linear interpolation of several correlation data from the PN PEMS and the test cell particle counter plotted in double-logarithmic scale (upper figure) and in linear scale (lower figure).

Fig. 4. PN PEMS and PM PEMS sensor concentrations for a laboratory test representing on-road driving of a DI-gasoline Euro-5 vehicle. The PM PEMS graph is shifted upwards for better visualization. Both signal traces are qualitatively in good agreement, the PN-soot-ratio is $1.5 \times 10^{12} \, \#/mg$. 
alignment is realized by adjusting the first increase of the PN concentration signal to the first increase of the CO signal that is provided by the Gas PEMS and already aligned with the exhaust flow.

4.2. Trip selection

One urban and one mainly Autobahn route were chosen as PEMS evaluation trips. The urban route leads through the city center of Aachen mostly with a maximum speed of 50 km/h and some short segments of 70 km/h. The second route consists of a fairly long Autobahn segment and some rural segments in the surroundings of the city of Aachen, Germany, with a maximum speed of 100 km/h. One complete PEMS evaluation run consists of twice the urban route and once the Autobahn route, resulting to a run time of about 90 min and an equal distance share between urban, rural and Autobahn segments.

For cold start tests the urban route was driven at different ambient temperatures ranging from 8 to 28 °C. Urban hot starts as well as Autobahn trips were performed right after the cold start test in order to begin the measurements with a fully warmed-up engine under otherwise similar ambient conditions.

4.3. Results

4.3.1. Driving dynamics

In this section the driving style of the conducted PEMS trips is compared to the style of the WLTC 5.3 and the euroFOT database, respectively, which are supposed to reflect normal driving. The parameters relative positive acceleration (RPA), average positive acceleration (APA), mean engine speed, and the idle fraction were chosen to characterize and quantify different driving styles. Severe driving was carried out by stronger acceleration, later braking, and higher maximum speed on the Autobahn (180 km/h). An overview of the present driving dynamics is shown in Fig. 6, the bar height represents the mean and the range bar the standard deviation for each parameter.

Both RPA and APA show increases from normal to severe driving, which is most significant for Autobahn driving. For urban trips mean engine speed and idle fraction are rather similar for both driving styles, probably due to the large dependence on traffic situations especially in the city center with numerous traffic lights.

![PN real world instrumentation consisting of a PN-PEMS, a PM PEMS, and an EFM controlled by a Gas PEMS.](image-url)
and other road users. On the Autobahn the mean engine speed is generally higher mainly due to higher average velocities.

The WLTC 5.3 is a chassis dynamometer driving cycle that is supposed to represent typical driving conditions (Tutuianu et al., 2013). In Fig. 6 urban RPA, APA and idle fraction of the present PEMS trips are generally higher and corresponding Autobahn parameters are lower than the parameters of the WLTC 5.3. This is expected as the WLTC 5.3 contains urban, rural as well as Autobahn segments.

The euroFOT database contains data of numerous trips that were collected in the framework of a large EU research project and that were driven by independent individuals with their private cars in everyday life (Benmimoun et al., 2011). The bars in Fig. 6 are calculated using a data-subset of trips with the same engine as in the PEMS test car but with manual transmission. Compared to the WLTC 5.3, RPA, MPA and idle fractions are similar for the euroFOT data; they are again within the present urban and Autobahn PEMS test data. The mean engine speed is higher than the PEMS values, probably because the cars reflected in the euroFOT database had a manual transmission so that the gear shifts occurred at higher engine speed.

For urban cold start tests the vehicle was soaked outside over-night to fully adjust to ambient conditions. The test started with a cold engine. In Fig. 6 the driving dynamics of cold and hot start tests show similar values, indicating a similar driving style.

The comparison of the driving dynamics of the PEMS trip data to WLTC 5.3 and euroFOT parameters demonstrates that the present “normal” driving style of the PEMS trips is within reasonable ranges. “Severe” driving, however, shows much larger values, as expected (especially on the Autobahn), indicating a driving style that is not representative for normal driving.

4.3.2. PN-PM-correlation

The on-road performance of the PN PEMS system was investigated with the soot measurement unit of the PM PEMS as an independent particle measurement method running in parallel with the PN PEMS. The target of this experiment was a comparison of the PN-to-soot-ratio calculated from on-road trips with data from several chassis dynamometer tests (see chapter 3).

For the PN-to-soot correlation only trips at ambient temperatures between 15 and 28 °C were considered in order to be reasonably comparable with regulated test cell temperatures of approximately 22 °C. The resulting correlation is shown in Fig. 7.

There is a good linear relation between PN and soot with a coefficient of determination $R^2 = 0.93$. The slope of the regression line represents the mean PN-to-soot-ratio. For the investigated vehicle a value of $1.1 \times 10^{12}$ particles per mg soot was determined, which corresponds well to chassis dynamometer cycles (blue squares in Fig. 7) as well as to literature values, as already mentioned in Section 0. This confirms a comparable performance of the PN PEMS operated in the vehicle driving on the road and in the laboratory.

4.3.3. Repeatability and temperature dependence

Several urban (with and without cold start phase) and Autobahn trips were performed, partly driven in a severe driving style for comparison purposes with normal driving style trips. An overview of the PN emissions is depicted in Fig. 8 in comparison to chassis dynamometer cycles and other PN data obtained from literature test cell results. In this plot the bar height and the range bar represent the mean PN emission and the standard deviation, respectively.

Driving style is an important parameter with a strong impact on the PN emission. Urban tests show just a small increase of PN from normal to severe style. This is in-line with the similar driving dynamics discussed in Section 4.3.1. The Autobahn trips show a much larger increase of PN from normal to severe driving because of much larger accelerations, higher velocities and higher power demand. Applying the severe driving style on the Autobahn, almost ten-fold higher PN emissions as compared to the normal driving style on the same route were observed. It is pointed out though that this driving style is not at all representative for normal driving.

Fig. 8 also shows the PN emission data for urban PEMS trips including the cold start phase obtained within an ambient temperature range from 8 to 28 ºC. The PN values including the cold start phase are larger than the “urban normal” data with a large range width and a coefficient of variance of about 50% indicating a large temperature dependency. The temperature trend of PN emissions is discussed in more detail in Section 4.3.4.

The PN PEMS results are compared to data from laboratory cycles representing on-road driving, and to test cell results from literature (Zhang et al., 2010; Braisher et al., 2010; Giechaskiel et al., 2012). On-road PN emission data are within the same range as values obtained from test cycles, whereas separate cold start emissions and severe driving style lead to elevated emission values.
Fig. 8. PN emission data of several PEMS trips separated by driving style and trip type compared to laboratory cycles and literature values.

Fig. 9. Comparison of one cold start (black trace) and one hot start (light grey trace) at 21 °C ambient temperature driven in normal driving style illustrating the cold start PN emission peak during the first 2 km.

Fig. 10. PN emissions categorized into cold start phase and post cold start phase. The cold start phase fraction is the ratio of PN emitted during the cold start phase to PN emitted during the complete test trip.
as expected.

4.3.4. PN emissions during cold and warm starts

In this section the cold start effect is investigated concerning PN emissions. Fig. 9 shows the time traces of one cold and one warm start at an ambient temperature of 21 °C, both trips have been conducted in a normal driving style as described in Section 4.3.1. There are increased PN emissions during cold start that last for a maximum travel distance of 2 km; further on the cold start emissions decline rapidly to the same level during both trips. In this example, the cold start accounts for about one third of the total PN emissions generated during the entire trip.

The evaluation and quantification of the cold start effect is performed by calculating the PN emissions for the cold start phase and for the post cold start phase. The end of the cold start phase is defined as the engine temperature reaching 70 °C, which is common for heavy duty test procedures. In Fig. 10, the integrated PN emission data are plotted against the ambient temperature.

For the investigated vehicle, the PN emission levels of the post cold start phase are independent of the ambient temperature at a constant level of about 4 × 10¹² #/km. The PN emissions of the cold start phase increase at lower ambient temperatures which is most probably caused by the longer warming-up period of the engine. Compared to the post cold start values, the cold start effect accounts for a factor of three higher emission levels at 28 °C and more than one order of magnitude at 10 °C ambient temperature. Considering the single data point at 8 °C as an outlier, a linear regression yields a slope of −1.5 × 10¹² #/°C, with a very poor coefficient of determination R² of 0.28. It is concluded that this trend needs to be verified with a larger number of measurements in the low temperature range and a larger number of vehicles.

In Fig. 10 the ratio of PN emitted during the cold start phase and during the complete test trip is shown. The PN cold fraction increases with lower ambient temperatures, ranging from 0.4 to 0.9. This result suggests that the cold start phase may become the main contributor to PN emissions, at least at low ambient temperatures. However, this ratio strongly depends on the total trip distance travelled. The ratio for the cold fraction value is in agreement with literature values derived from chassis dynamometer tests. Braisher et al. (2010) found that at least 77% of the PN was emitted in the first phase of the NEDC due to the cold start effect, while in the present study a percentage of about 60% at 22 °C is reported (see Fig. 10). The lower cold start contribution found in this study is reasonable because during on-road driving the share of particle production from accelerations during warmed-up engine condition is larger than in the NEDC.

5. Summary and conclusions

Real Driving Emissions are planned to be implemented in Euro-6c legislation applicable in 2017/2018 including the regulation of NOₓ while a PN procedure may be introduced at a later stage. In the present paper the performance of a PN on-road measurement system was investigated.

The PN PEMS employed has a limit of detection of 1 · 10¹⁰ #/km. In the test cell a good correlation was determined with a systematic deviation of around 20% in comparison to an R-83 PMP reference setup. Simultaneous soot measurements were conducted using a PM PEMS both in the test cell and during on-road testing. The obtained very similar PN-to-soot ratios in the range of 1 · 10¹² to 2 · 10¹² #/mg demonstrate the suitability of the PN PEMS for on-road measurements.

Numerous PEMS on-road test trips have been conducted including PN measurements. Driving parameters are consistent with the WLTP and the euroFOT databases indicating a driving style in a normal range. On-road PN emission data are within the range of laboratory cycle data and are thus representative for on-road driving as well as comparable to test cycle data reported in literature. Severe driving style resulted in a PN increase of up to one order of magnitude. A more severe driving style during urban driving has only a small effect on PN emissions. In urban districts the repeatability of on-road tests was naturally strongly affected by randomly changing traffic situations. A PN cold start effect is found that is increasing with decreasing temperatures, ranging from 5 · 10¹² to 1.5 · 10¹³ #/km within an ambient temperature range of 8–28 °C. The contribution of PN emissions during cold engine operation during on-road testing is smaller than in previous NEDC studies. This contribution strongly depends on the overall travel length. However, for a more precise analysis, further PEMS measurements need to be conducted, widening the range of vehicles and also environmental conditions.

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