Particulate Emissions of Gasoline Vehicles and Influence of the Sampling Procedure

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Particulate Emissions of Gasoline Vehicles and Influence of the Sampling Procedure

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ABSTRACT

In this paper, we present the results of an experimental study on particulate emissions of gasoline vehicles. The objective of the project was to investigate the particulate emissions on the basis of number and total mass and to gain experience in the influence of the sampling method on the results. The measurements were carried out with three passenger cars at a chassis dynamometer. Two vehicles with premixed combustion and one direct injection engine were tested at constant loads and driving cycles. For the aerosol sampling we used a standard CVS system, an ejector and a rotating disk unit. The samples were analyzed by SMPS and ELPI. Samples for gravimetric analysis were taken downstream of the CVS tunnel and from a mini tunnel.

The results show that all three vehicles produce significantly less particulate in number and mass than a common diesel vehicle. Increased particle emissions were observed for the direct injection vehicle during the driving cycles and for the premixed engines for rich air-fuel equivalence ratios. It was found that the sampling method has a rather high influence on the results of the total number and the number size distribution. The result of the comparison between ELPI and SMPS depends strongly on the particle density, which is in general not known.

INTRODUCTION

Transportation is considered as one of the most important sources of fine particle emissions. This is because diesel engines are well known for their soot emission. As a consequence the emission of particulate mass has been limited by legislation for diesel vehicles for many years. In contrast to heavy-duty vehicles most passenger cars are equipped with spark ignition engines fuelled with gasoline (Switzerland: 95%). For gasoline vehicles, no legislation has been enacted for the emission of particulate matter. This is a comprehensible decision as the mass found on a filter by gravimetric analysis is very low compared to diesel engines. In recent years health issues related to particulate

immission has become of increased concern. Epidemiological studies and experiments with animals force this interest. Most of the studies are based on particle mass, e.g. PM_{10} , $PM_{2.5}$, [1]. However, it is supposed that the particle number could be an additional or even better indicator of adverse health effects [2]. This is explained by the thesis that these very fine particles have easier access to the human lung and that every individual particle causes an irritation in the alveolus.

Based on this background a new assessment of particle emission of gasoline vehicles has to be established. This is because a low mass emission does not conclusively result in low number emission, particularly if the size of the particles is very small. Therefore, knowledge of the particle number size distribution of an aerosol is of crucial interest.

This paper presents data from three gasoline fuelled passenger cars of different technology. The cars were tested at different driving conditions to enlarge the knowledge about particulate emission of spark ignition engines. In addition, three different dilution systems and three different measurement methods were tested to determine the influence of the methodology. The study could help to assess the relevance of the contribution of the gasoline fleet to the pollution of transportation.

EXPERIMENTAL

EXPERIMENTAL SETUP

Particle Measurement systems

Three methods were used in this study to quantify the particle emissions from gasoline vehicles:

Gravimetric analysis The gravimetric analysis was carried out with a CVS-system following the European regulations. In addition samples were taken from partial flow dilution unit (mini tunnel) for comparison.

SMPS The Scanning Mobility Particle Sizer (SMPS) measures number size distributions on the basis of electrical mobility for size discrimination and light

scattering for counting. The instrument covers a size range between 15 and 630 nm. Further details of the method are described at [3]. For a full size spectrum a time period of approximately one minute is needed. This applies only for constant operation modes but not for driving cycles. Particle values with a time resolution of about one second can be obtained for the total number or a very narrow size range.

ELPI The Electrical Low Pressure Impactor is constructed similar to a conventional cascade impactor. The ELPI consists of 13 stages, which covers a size range from 35 nm to 9 μm . The quantity of the particles is determined by measuring the charge on the stage caused by the charged particles. The particles acquire a well-defined monopolar charge in a corona charger upstream of the stages. By calibration of each size class the charge is linked to a number of particles. Further details of the method are described at [4]. With ELPI a time resolution of a few seconds being achieved, it is possible to follow a transient driving cycle. In our experiments the current from the five upper stages were so low that they were not considered for the data evaluation.

Dilution systems

For the particle measurements different dilution methods were applied and compared with each other:

CVS-system Particle samples for number and mass measurements were directly taken from the tunnel of the Constant volume sampler (CVS) as it is used for regulation tests. The dilution ratio depended on the vehicle and the load, but was always higher than 9. In some cases we applied a second dilution stage (ejector) downstream of the CVS-system for the number measurements. A partly heated tube of 5 m length connected the exhaust pipe of the vehicle to the tunnel.

Ejector based dilution unit Inside this system particle-free pressurized air is mixed with the aerosol sample. A pressure drop at the ejector nozzle achieves a homogeneous mixing and constant dilution ratio. The dilution ratio of our system was 14. The ejector was only applied in combination with the CVS system.

Rotating disc dilution unit This dilution sampling method is based on the transport of small discrete aerosol portions from raw aerosol stream into a particle free gas stream, the sample flow. The exchange of the volume is done by small cavities in a rotating disc that has contact to both channels. Further details of the method are described in [5]. In our experiments dilution ratios were set between 40 and 110. The probe was installed about 0.7 m downstream of the exhaust pipe.

Mini tunnel This dilution method is based on the mixing of a small aerosol stream with particle-free dilution air in a mini tunnel. The total flow and dilution airflow is controlled by mass flow meters to fix the dilution rate. In our experiments dilution ratios were set to 6.7 or 13.3. The probe was installed about 1 m downstream of the exhaust pipe.

Thermo desorber

To obtain information about the composition of the fine particles we apply in our experiments a thermo desorber. The thermo desorber consists of two parts: a temperature controlled heated tube and a cooled part filled with active charcoal. In the first part, volatile material will evaporate depending on the temperature and re-condenses in the cooled part. Due to the larger surface area, most of the condensation will take place on the charcoal and not on the surface of the particles again. By comparison of particle distributions measured at different temperatures, one obtains information about the volatile fraction of the particles. Particles produced by homogeneous condensation will completely vanish when the evaporation temperature is exceeded. In this study the thermo desorber was set on a fixed temperature of 300 °C. Measurements with and without TD were carried out for comparison. Calibration measurements with solid particles revealed losses of about 30% at a temperature of 300 °C by thermophoresis and diffusion. These losses were corrected in all measurements with TD shown in this paper.

Test rig

The tests with the vehicles were carried out on a single roll chassis dynamometer equipped with full flow dilution tunnel and analysis instruments for the regulated pollutants. Figure 1 shows the schematic of the experimental set-up.

Figure 1: Schematic of the experimental set-up

Vehicles

Three gasoline passenger cars were tested for this work: Two vehicles with premixed combustion but different engine displacement and one direct injection engine which has the same engine displacement as the larger premixed engine. All vehicles were equipped with three way catalytic converters and were fuelled with gasoline with a research octane rating of 95 and which fulfill the EN228 specifications. Table 1 outlines the main features of the vehicles.

Vehicle	IDI1.8	IDI1.4	DI1.8
Displacement [cm ³]	1795	1389	1834
Injection	Multipoint (indirect)	Singlepoint (indirect)	Multipoint (Direct)
Year of manufacture	1995	1997	1997
Odometer [km]	19400	22100	14400
Number of cylinder	4	4	4
Number of valves per cylinder	4	2	4
Rated power [kW]	103	44	92
Rated engine speed [rpm]	6000	5400	5500
Max. torque [Nm]	175	106	174
at engine speed [rpm]	4500	3000	3750
turbo charger	no	no	no
EGR	no	yes	yes
TWC	yes	yes	yes
Unladen weight [kg]	1220	895	1260

Table 1: Details of test vehicles

EXPERIMENTAL METHODS

The tests were carried out at four different constant modes and at three different driving cycles including a cold start and a high-speed sequence. The European driving cycle (EDC) was run according to Euro III regulations, i.e. without 40 s idle before the start of the measurement. Details of the modes and cycles are listed in Table 2 and Table 3, respectively. Filter sampling for gravimetric analysis and measurements with two SMPS systems and an ELPI were carried out in parallel during the test procedure. In addition the emission of the regulated pollutants were measured to ensure the normal operation of the vehicles. At constant speeds, the particle number measurements took place at least over the time period of ten minutes after the oil temperature of the engine was stable.

Operation mode	speed v / km/h	Gear	Load
1	50	3	road load
2	80	5	road load
3	120	5	road load
4	80	5	full-load

Table 2: Constant driving modes

Driving Cycle	T _{oil} at start	Speed [km/h]		Time period	Distance
	[°C]	v _{MEAN}	v _{MAX}	[mm:ss]	[km]
EDC	20 ±5	34.5	120	19:31	11.0
EDC warm	80 ±5	34.5	120	19:31	11.0
BAB	80 ±5	116.6	160	16:43	32.5
Special cycle	80 ±5	68.4	120	17:48	20.3

Table 3: Driving cycles

RESULTS

COMPARISON OF VEHICLES

Gravimetric analysis

The results of the gravimetric measurements for the different driving conditions are shown in Figure 2. The samples were taken from the CVS tunnel according to the regulation. A balance (Mettler-Toledo MT5) with resolution of 1 µg was used to determine the load on the filter. However, in some experiments the filter load was below 20 µg and showed a poor repeatability. Therefore, it is not possible to present reliable emission data below 1 mg/km. The particle mass of the three gasoline vehicles in this study were significantly lower compared to Diesel passenger cars, which is limited to 80 mg/km and 100 mg/km for IDI and DI engines in Europe. As expected operation higher loads generally results in higher emissions for premixed engines. However, this result does not apply to the direct injection engine. At constant speeds we observed the lowest emission for 120 km/h. For both 1.8 l - engines the air-fuel equivalence ratio for the combustion was in the range of 0.9 at 80 km/h under full-load conditions, which resulted in higher emissions. For the other steady state modes the direct injection engine was in a lean combustion mode with $\lambda \approx 1.6$. Comparing the warm EDC and the highway cycle the DI vehicle does not show a significant increase in mass concentration for the high-speed cycle in contrast to the IDIs.

Figure 2: Particle mass emissions of the vehicles for different test runs; n.m.: not measured

Number size distributions

Steady state conditions In parallel with the gravimetric measurements, number size distributions (NSD) were measured with SMPS. The sample was drawn from the raw gas channel about 70 cm downstream of the exhaust pipe and diluted with the rotating disk unit by dilution factor $DF = 40$. The results of the measurements with and without thermo desorber are shown in Figure 3. The levels are expressed in logarithmic scale. The number concentrations vary more than two orders of magnitude depending on the vehicle and the load, whereas no large shifts in size can be observed. Similar trends can be observed in the number emissions as for the mass emission. The premixed engines show with few exceptions increased emissions with higher loads. The DI engine shows the lowest particle number emission at 120 km/h. This is in good agreement with the mass measurements. The premixed engines show with few exceptions increased emissions with higher loads. The DI engine shows the lowest particle number emission at 120 km/h. This is in good agreement with the mass measurements.

Measurements with a thermo desorber (TD) at 300 °C were carried out to give a fast qualitative indication of the volatile fraction of the particles. The measurements reveal a larger reduction in particle number by evaporation for lower loads. This corresponds to common experience by chemical analysis of the higher SOF fraction in the particle composition at lower loads. At 80 km/h at full-load the NSD for the IDI1.4 shows a strong increase below 40 nm that vanishes when the TD at 300 °C is inserted in the sampling line. This indicates that these particles are composed of condensed material that could be generated in the sampling line.

Figure 3a: Number Size Distributions at 50 km/h and 80 km/h; solid lines: w/o TD; w/o lines: with TD at 300 °C.

Figure 3b: Number Size Distributions 120 km/h and 80 km/h at full load; solid lines: w/o TD; w/o lines: with TD at 300 °C.

Driving cycles Figure 4 shows the total particle number per second emitted by the three vehicles during the European driving cycle (EDC). The levels are expressed in logarithmic scale. The samples were sucked from the CVS tunnel in an ejector and once more diluted. The particle concentration was determined by a CPC. With exception of the starting phase and the high-speed phase at the end of the cycle the DI engine emits significantly more particles than the both IDI engines. In the start phase both IDI engines show increased emissions in contrast to the DI vehicle. A drastic increase in emission at 120 km/h phase is observed for the smaller IDI engine, which is in good agreement to the steady state tests. For comparison the emissions of a diesel vehicle with an IDI1.9l engine is added. It can be

seen that the emissions of the DI vehicle are one order of magnitude lower and the IDI vehicles 2-3 orders of magnitude lower than common Diesel vehicle.

Measurements with a thermo desorber - revealing the non-volatile fraction - resulted in similar patterns for the particle emissions (diagram not shown). However, the peak at 120 km/h for IDI1.4 was reduced by almost a factor of 100.

EDC runs with warm engine start showed that only the emissions in the first of the four sequences of the urban phase were significantly reduced compared to the runs with cold engine start. Consequently, a cold start seems to affect only the first 5 minutes of a cycle.

In Figure 5 the total particle number emissions are shown for the German highway cycle (BAB). The high speeds at this cycle cause the highest emissions for the small IDI engine. These measurements were carried out with the ELPI instrument sucking the sample directly from the CVS tunnel. The lower size detection limit of the ELPI is $d_p = 35$ nm compared to 7 nm for the CPC. Therefore the "total number" measured with ELPI is not comparable with results measured with CPC, because the presence of particles below 35 nm in the exhaust gas of I.C. engines can not be ignored.

For a special created cycle the effect of acceleration at different speed levels were studied. The results measured with CPC are shown in Figure 6. Both 1.8 l engines do not show a significant increase of the emissions at higher constant phases but the emissions are dominated by the acceleration phases. Only the smaller IDI vehicle shows an effect from the different load levels. At the 100 km/h level the particle concentration is drastically increased. Acceleration phases lead to a further increase of the emissions.

The number size distributions for different driving cycles are shown in Figure 7. The columns represent the concentration per size channel indicated by the midpoint aerodynamic diameter. The measurements were made with the ELPI instrument. The aerosol was sampled from CVS tunnel. Again, the plotted levels are expressed in logarithmic scale. No significant differences in the distribution are found between the different vehicles and cycles. Only the concentration level varies for the different configurations indicating higher emissions for the BAB cycle and only a small reduction in concentration due to the warm start in the EDC compared to the official EDC with cold start.

Figure 4: Total number emissions during EDC measured with CVS and ejector for dilution and CPC for counting

Figure 5: Total number emissions during the BAB cycle measured with CVS tunnel and ELPI

Figure 6: Total number emissions during a special cycle measured with rotating disc dilution unit and CPC

Figure 7: Number size distribution integrated over the cycle as measured with the ELPI; d_p in aerodynamic diameter

COMPARISON OF MEASUREMENT METHODS

The comparisons between the different measurement methods we carried do not claim to be a comprehensive study of this item. Our objective was to get a qualitative information of the accuracy of our measurements. Measurement methods for particulate matter can be subdivided in two areas: sampling/conditioning/dilution and classification/detection. We investigated a few comparisons with examples concerning both areas:

Comparison of dilution methods

The experiments were carried out at 50 km/h and 80 km/h full load with the IDI1.8I-vehicle. Number size distributions were measured with SMPS with and without thermo desorber using three different dilution systems: CVS tunnel, rotating disk dilution unit and mini tunnel. In some cases an ejector was applied in combination with the CVS system. Figures 8a and 8b illustrate the effect of the dilution system. Differences in concentration were found up to almost a factor of two for the high load mode. For the lower load mode, the agreement was even worse. Measurements with TD at $T = 300^\circ\text{C}$ result in reduction of the total number of 33-41% for the high load and 68-81% for the low load and do not depend on the dilution system. In Figure 8a it can be seen for 80 km/h full load that a lower number is accompanied with a larger size of the mode of the distribution. This effect could be caused by agglomeration. In addition, examples of the repeatability within one system are shown for the CVS and the rotating disc systems in Figure 8a. The NSD –indicated by identical lines – were measured on different days and an acceptable repeatability with and without TD was achieved.

Figure 8a: Comparison of different dilution units for steady state mode 80 km/h at full-load; NSD measured with SMPS and with and without thermo desorber.

Figure 8b: Comparison of different dilution units for steady state mode 50 km/h at road load; NSD measured with SMPS and with and without thermo desorber.

Gravimetric analysis

In Figure 9 the results of the comparison between CVS tunnel and mini tunnel are presented for the filter sampling. The measurements were carried out in parallel. The probe of the mini tunnel was installed about 1 m downstream of the exhaust pipe. The dilution ratio for the mini tunnel was constant and set to 6.7 or 13.3.

Figure 9: Comparison of total mass results measured with CVS and mini tunnel

The dilution ratio for the CVS varied between 9 and 47 depending on the vehicle and driving mode. Only measurements with more than a certain mass on the filter were considered, which reduced the number of samples significantly. No clear trend in the results can be observed. The differences range from about 5% up to almost a factor of 2. It is assumed that mass emissions generally were too low to obtain good reproducible results by the applied methods.

Comparison of NSD measured with SMPS and ELPI

It has to be mentioned that the size classification of both instruments is based on different physical properties. Both instruments do measure an equivalent diameter that is different for non-spherical particles from the geometric diameter. With SMPS the electrical mobility diameter is measured. Here, particles of the same geometric size and shape but different density are detected in the same size class. The ELPI instrument measures the aerodynamic diameter, which depends on the density of the particles. This crucial difference has to be taken into account for a comparison.

Figure 10: Comparison of NSD measured with SMPS and ELPI; sampling from CVS, vehicle DI1.8I at 120 km/h

Figure 10 shows, as an example, a comparison between both instruments for a constant driving mode. The agreement is rather poor when the aerodynamic diameter, i.e. particle density of 1 g/cm³, is plotted for the ELPI. Similar to Keskinen et. al. [6], we assume a particle density to convert the distribution to the more comparable Stokes diameter. The best agreement was found for a particle density of 0.6 g/cm³. Such low values can be explained by the agglomerate structure of the particles and has been reported by [6], [7], for instance. However, lower densities than 1 g/cm³ shift the measurement range of the ELPI to larger sizes. Due to the shift no clear mode of the NSD is detected with the ELPI.

Comparison CPC – ELPI during driving cycle

Figure 11 shows a sequence of an EDC driven by IDI1.8l vehicle. The total number concentration per second is plotted. An acceptable agreement between the instruments was observed for all vehicles and cycles. During constant phases the difference were found to be within the range of 30%, whereas the peak values of the ELPI during acceleration were generally 60% higher. The shorter response time and higher flow rates of the ELPI could explain this. However, it has to be taken into account that the ELPI instrument does not measure particles below $d_p = 35$ nm in aerodynamic diameter and a particle density of 1 g/cm^3 was used.

Figure 11: Comparison of total number concentration measured with SMPS and ELPI during a sequence of EDC driven with vehicle IDI1.8l; sampling from CVS

DISCUSSION

Significantly higher particulate emissions were observed for the tested direct injection engine than for the premixed engines at low and moderate constant loads and in the cycles. The emission levels were found to be unstable at some driving modes, which could indicate unstable conditions for the combustion in the DI engine. The lowest emission level was found at 120 km/h (5th gear), indicating good combustion conditions in this mode. At these conditions the air-fuel equivalence ratio was determined to be 1.6 by calculating from the CO_2 , O_2 and CO concentrations.

At transient conditions, the general pattern of the time course looks different for the different engine concepts. The IDI gasoline engines show a low ground level and strong increase during acceleration phases and high loads whereas the diesel engine shows a high ground level and significant lower increase with acceleration and load. The pattern of the DI gasoline engine looks like a mixture of both and shows a concentration level between the diesel and the IDI gasoline engines. This indicates a more diesel-like combustion of the DI engine.

The comparison between the CVS and the mini tunnel for gravimetric analysis do not show satisfying results in some test runs, which can not be clearly explained.

However, the number of samples was too small to give a complete conclusion. At EMPA a very extensive parameter study on partial flow dilution systems was carried out for gravimetric emissions of heavy-duty diesel engines. The results will be published in [8]. It is evident that more experiments have to be carried out to clarify the suitability of the partial flow system for gasoline engines.

Large differences in number concentration were found for different dilution methods. Measurements with a thermo desorber at 300°C show about the same percentage of reduction in total number for the different methods. So the discrepancy can not be simply explained by homogeneous condensation of volatile matter inside the sampling line due to supersaturating. As the highest concentration were found with rotating disc dilution unit (highest DF, lowest τ) and the lowest with the CVS (lowest DF, highest τ) we assume that the differences could be mainly explained by agglomeration processes. Nevertheless, parameters as temperature in the sampling line and dilution unit, residence time of aerosol at high concentration and dilution ratio seems to have a significant affect on the result.

A comparison of number size distribution measurements between SMPS/CPC and ELPI is very difficult. The results depend largely on the particle density, which is, in general, not known. The large discrepancies we found in our comparison could result from the fact that the sizing is based on different physical particle properties. In addition, the sizing also affects the particle counting of ELPI, as the number is determined by integrating the current caused by the charge on the particles. The charge, however, is a function of a particle size, which is different from equivalent aerodynamic and electrical mobility size [9]. In principle, this inaccuracy affects the SMPS as well - by combining aerodynamic diameter of pre-impactor and mobility diameter by electrical deflection - but to a significantly lower extent. Concerning the access and deposition in the human lung, there is not one single size parameter that describes the particle motion satisfactorily. The aerodynamic diameter - measured by ELPI - is of larger relevance for larger particles (inertial motion) whereas the electrical mobility diameter (Brownian motion) - measured by SMPS - is the more important parameter for particles smaller than a few hundreds of nanometer. Consequently both sizing methods do have their application.

CONCLUSION

We draw the following conclusions from the results of our study:

- All three tested gasoline vehicles do emit significantly less particles in mass and number than common diesel vehicles.
- As expected, the air-fuel equivalence ratio during combustion has a crucial effect on the particulate emissions of gasoline engines. It is evident that fuel

rich combustion does cause increased particle emissions by incomplete combustion. But even at an air-fuel equivalence ratio of 1 increased particle levels were observed for the smaller engine at high loads.

- The measurements on the tested direct injection engine reveal, at low and moderate loads, significantly higher particulate emissions than for the premixed engines. From this result we conclude that the new technology of direct injection for gasoline engines might become a more relevant particle emission topic.
- Particle mass measurements, as carried out according to the regulation for diesel vehicles, are at the lower detection limit and show large scattering. Measurements with a partial flow unit do not show any improvement and in some cases a significant discrepancy to the measurements with the CVS system.
- The large effect of the sampling and dilution method on the results of the particle number measurements once more reveal the poor reproducibility of fine particle number measurements, in principle. However, the repeatability of the measurements is acceptable.
- A direct comparison between SMPS and ELPI is very difficult, because sizing and counting are based on different methods. A calamity of the method applied by ELPI is the link between size and number due to the charging efficiency.

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REFERENCES

1. Dockery D. W., et al. "An Association between Air Pollution and Mortality in Six U.S. Cities" *The New England J. of Medicine*, Vol. 329, 24, 1754-1759, 1993
2. Peters A. et al, *Am J. Respir. Crit. Care Med.*, 155, 1376-1383, 1997
3. Knutson E. O., Whitby K.T. "Aerosol Classification by Electric Mobility: Apparatus, Theory, and Applications" *Aerosol Sci.*, 6, 443-451, 1975
4. Keskinen J., Pietarinen K., Lehtimäki M. "Electrical Low Pressure Impactor", *J. Aerosol Sci.* 23, 353-360, 1992

5. Hueglin Ch., Scherrer L., Burtscher H. "An Accurate, Continuously Adjustable Dilution System (1:10 to 10⁴) for Submicron Aerosols" *J. Aerosol Sci.*, Vol. 28, No. 6, pp. 1049-1055, 1997
6. Keskinen J. et al. "Estimation of Effective Density of Diesel Particles" *J. Aerosol Sci.*, Vol. 29, Suppl. 1, S1007-S1008, 1998
7. Skillas G., Siegmann K., Baltensperger U. "The Density and Fractal-Like Dimension of Particles Sampled from a Laminar Diffusion Flame" *J. Aerosol Sci.*, Vol. 29, Suppl. 1, S1277-S1278, 1998
8. Schweizer Th. and Stein H. J. "A New Approach To Particulate Measurement On Transient Test Cycles: Partial Flow Dilution as Alternative to CVS Full Flow Systems" SAE technical paper 2000-01-1134
9. Moisio M. "Real Time Size Distribution Measurement of Combustion Aerosols" PhD thesis, Tampere University of Technology, Tampere (FIN), pp. 64-74

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BAB	Bundesautobahnfahrzyklus (German highway driving cycle)
CPC	Condensation particle counter
CVS	Constant volume sampler
DF	Dilution factor
DI	Direct injection
DMA	Differential mobility analyzer
d_p	Particle diameter
EDC	European Driving Cycle
ELPI	Electrical Low Pressure Impactor
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt (Swiss Federal Laboratories for Materials Testing and Research)
IDI	Indirect injection
λ	Air-fuel equivalence ratio for combustion
NSD	Number size distribution
SMPS	Scanning Mobility Particle Sizer
τ	Residence time in undiluted sampling system
TD	Thermo desorber