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ORIGINAL PAPER

Roller dynamometer particle immission* measurement

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Abstract

Urban traffic is a significant contributor of particulate matter to the environment (Kessinger et al. in https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/hgp_luftqualitaet_2020_bf.pdf, 2021). Hence, there is a high interest in the measured data of roadside immission measurement station. In the federal state Saxony (Germany), the State Office for Environment, Agriculture and Geology (LfULG) is responsible for supervision of the air pollution. In a joint project, the LfULG, the Leibniz Institute for Tropospheric Research (TROPOS) and the Chair of Combustion Engines and Powertrain Systems of the Technical University of Dresden (Lehrstuhl für Verbrennungsmotoren und Antriebssysteme, LVAS) measured the particulate immission* from a selection of passenger cars in an "environment simulation" Weinhold et al. (https://publikationen.sachsen.de/bdb/artikel/36768q, 2020). Especially direct injection spark ignition engines, DISI, without particle filter have a high particulate matter emission, depending on the operating condition. However, an increase of the particulate matter immission due to the rising market penetration of DISI engines was not measurable at the immission measurement stations of LfULG. To investigate the effect of vehicle exhaust emission and immission, an experiment was developed to measure particulate matter immission similar to road conditions on a chassis dynamometer. Five used cars with different engines, exhaust after treatment systems and mileage were evaluated regarding their emissions and particulate immissions. Unexpectedly, a high amount of ultrafine particulate matter smaller 100 nm was found during the emission measurements, although the exhaust emissions were completely extracted to the CVS measurement system. It was concluded that these particles were assignable to break and tire wear. This paper summarizes the most important findings, the complete report is available in Weinhold et al. (https://publikationen.sachsen.de/bdb/artikel/36768q, 2020).

Keywords Particle immission · Particle emission · Roller dynamometer · Environment simulation · Brake and tire wear · Non exhaust emission

List of symbols

dN	Particle concentration (#/cm^3)
D_p	Midpoint particle diameter (nm)

Abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation particle counter
CVS	Constant volume sampling system
DC	Direct current
DD	Dresden
DISI	Direct injection spark ignition
DPF	Diesel particle filter
GPF	Gasoline particle filter
Immission*	Characterizes the measured pollution in the test chamber that evolved from the point of emission
LfULG	Saxon State Office for Environment, Agriculture and Geology (Germany)
LVAS	Chair of combustion engines and powertrain systems of the technical university Dresden
MAAP	Multiangle absorption photometer
MPSS	Mobility particle size spectrometer
NEDC	New European Driving Cycle
NO_x	Nitrogen oxide
PID	Proportional–integral–derivative controller
PM	Particle matter
PMU	Particle measurement unit
PN	Particle number
SCR	Selective catalytic reduction

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SN	Serial number
T.HC	Total hydro-carbons
TROPOS	Leibniz Institute for Tropospheric Research
UFP	Ultrafine particles
UV	Ultra-violet radiation
WLTC	Worldwide Harmonized Light Vehicle Test Cycle

1 Introduction

The immission of particles is of great importance to human health. Roadside measurement stations try to assess the immission from traffic. However, there are correlations with various other factors, e.g., wind, solar radiation, building arrangement, geometries of urban canyons, etc. Statistically, there is a great influence of road transport on particulate immission. Especially black carbon, originating from the combustion of fuel in engines, is very relevant to health and considered to be cancerous. Particles smaller than 100 nm are defined as ultrafine particles (UFP), and have pulmonary and cellular patency [8]. The end of pipe particles from combustion engines have a wide size distribution with a maximum between 40 and 100 nm [1]. In Ref. [6], it is shown that the particle number concentration for particle diameters of 30–200 nm has decreased by 74% and for soot by 59% for the period from 2010 to 2016. This was attributed to the introduction of the diesel particulate filter. A new focus is on direct injection spark ignition engines, DISI, without particle filter, which was the reason for the introduction of the gasoline particle filter, GPF, with the emissions legislation Euro 6d-temp in September 2019. DISI engines before this date were delivered without filter. However, an increase in PM immission due to the rising market penetration of DISI engines before 2019 was not measurable at the immission measurement stations of the State Office for Environment, Agriculture and Geology (LfULG) of the federal state of Saxony (Germany). This project was devised to elucidate the context between engine particulate emission and immission.

After the emission from the tailpipe, the particle size distribution varies due to diffusion and coagulation processes. Since the intake of the road side immission measurement stations are usually about 3–10 m away from the street, much smaller particle number concentrations are detected than at the vehicle tailpipe. The evolution of the particles on their way from the point of emission to the point of immission measurement needs to be understood. Hence, a methodology was developed to reproduce a roadside similar particle immission with selected Euro 5 and Euro 6 vehicles on a conditioned chassis dynamometer [9]. In this methodology, the environmental influence (wind direction, solar radiation etc.) was excluded to understand the basic mechanisms of diffusion and coagulation without any further side effects. The test chamber was controlled such that the traffic density (i.e., the air pollution level) and dilution process could be reproduced. This was monitored by the concentration of carbon dioxide within the test chamber. For a first assessment, every vehicle was tested with in a Worldwide Harmonized Light Vehicle Test Cycle, WLTC, using a standard constant volume sampling system (CVS), to determine the condition of the engine and after treatment system. Then, the vehicle exhaust emissions during an urban velocity profile were ejected into the dynamometer chamber, instead of being extracted into the CVS system. The test chamber was conditioned at three different temperatures to reflect different seasons. The agreement with data from the immission measurement station was acceptable and a number of suggestions for an improved methodology were derived.

One unexpected result was the strong effect of tire and brake wear on the concentration of UFP and black carbon.

2 Test bench and boundary conditions

2.1 Emission measurement

A selection of second hand Euro 5 and Euro 6 vehicles was tested in a Worldwide Harmonized Light Vehicle Test Cycle (WLTC, regulation EU 2017/1151 [3]) irrespective of its original homologation cycle (NEDC or WLTC). The emission evaluation was performed with a constant volume sampling system, as shown in Fig. 1. The gaseous emissions were analyzed using a standard exhaust gas measurement system HORIBA Series 9000, including a chemiluminescence analyzer (for NO_x), flame ionization detector (for T.HC) and a non-dispersive infrared gas analyzer (for CO/CO_2). The particle mass was detected gravimetrically through filter extraction and the particle number was determined via a condensation particle counter (CPC). The air blower in front of the vehicle facilitates the velocity dependent engine cooling. The air conditioning system compensates for the heat flux of the engine into the test chamber and ensures the ambient conditions. The road resistance curves for each test vehicle were defined from coast down.

Euro 5 and Euro 6 vehicles are homologated corresponding to the most stringent set emissions legislation and did account for 53.4% [5] in 2019, in Germany. For the current experimental campaign, vehicles were selected from these two emissions classes, since they have the most modern methods of mixture formation (e.g., high pressure injection) and exhaust gas after treatment. Euro 5 spark ignition engines do not have a particle filter, thence a higher particulate emissions compared to the latest specification Euro 6d-temp engine with gasoline particulate filter, GPF, is expected. Especially direct injection engines were of

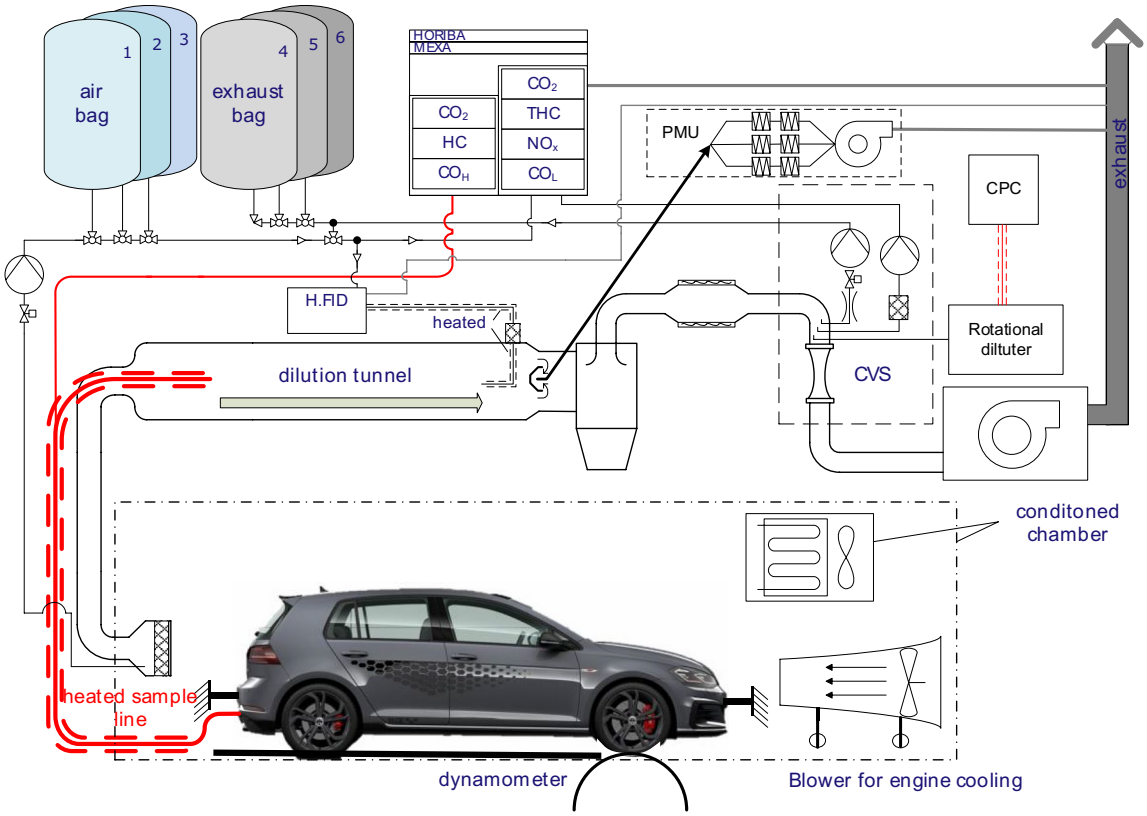

Fig. 1 Schematic illustration of the CVS system for emission measurements

interest. These engines on the one hand have very much improved fuel efficiency over port injection engines; on the other hand, their particulate emission is higher due to the much shorter mixture formation process. Thus, the following engine/after treatment configurations were tested, to represent the majority of the German vehicle fleet.

- Euro 6d-temp, 2.0 l spark ignition, direct injection engine with three-way catalyst and gasoline particle filter (GPF), front wheel drive, mileage: ~ 15,000 km.
- Euro 6c, 2.0 l diesel engine with diesel oxidation catalyst, selective catalytic reduction and diesel particle filter (DPF), front wheel drive, mileage: ~ 25,000 km.
- Euro 5, 1.6 l spark ignition, direct injection engine with three-way catalyst, front wheel drive, mileage: ~ 120,000 km.
- Euro 5, 1.5 l spark ignition, direct injection engine with three-way catalyst, front wheel drive, mileage: ~ 55,000 km.
- Euro 5, 2.0 l diesel engine with diesel oxidation catalyst and diesel particle filter, front wheel drive, mileage: ~ 115,000 km.

The results of the WLTC are shown in Table 1.

The emission verification in Table 1 shows that each of the tested engine and after treatment systems were working well. Thence the selected vehicles are deemed suitable for the immission simulation. However, the 1.4 l Euro 5 spark ignition engine, homologated in the NEDC, yielded a particulate mass which was 3.2 times higher than the WLTC limit. This particular vehicle was known to have a high amount of short range driving, and this can explain the high PM-emission level. Low engine temperatures during short range driving can cause deposits in the entire air- and exhaust path, which then are released at higher engine temperatures. During WLTC, especially in the extra high phase, the engine temperatures rise sufficiently for the release of deposits. The particulate filter of the particulate measurement unit, PMU, was intensively loaded during the high and extra high parts of the WLTC, which confirms the assumption. Also, the utilization of larger parts of the engine map during WLTC in comparison to the NEDC, generally leads to higher emissions. Nevertheless, this vehicle represents a large share of vehicles mainly in urban use and accordingly was determined to be part of the immission* evaluation. The evident limit exceedance of the Euro 5 Diesel engine regarding the NO_x-limit also can be traced to the use of larger parts of the engine map and higher dynamic load requests during WLTC compared

Table 1 Emission measurement results

Configuration	Euro 6c 2.0 l diesel engine	Homologation limit	Remark
Emission	Measured value in WLTC	In WLTC	[–]
mCO_2 [g/km]	136.2	No limit	Vehicle homologated in WLTC (Euro 6c)
mCO [mg/km]	8.0	500	After treatment: diesel oxidation catalyst, SCR-catalyst, DPF
$mHC + mNO_x$ [mg/km]	72.5	170	All emissions limits achieved
mNO_x [mg/km]	71.7	80	
PM [mg/km]	0.1	4.5	
PN [#/km]	1.70E + 10	6E + 11	
Configuration	Euro 6d-temp 2.0 l spark ignition engine	Homologation limit	Remark
Emission	Measured value in WLTC	In WLTC	[–]
mCO_2 [g/km]	157.9	No limit	Vehicle homologated in WLTC (Euro 6d-temp)
mCO [mg/km]	199.8	1000	After treatment: 3-way catalyst, GPF
mHC [mg/km]	13.6	100	All emissions limits achieved
mNO_x [mg/km]	21.1	60	
PM [mg/km]	1.5	4.5	
PN [#/km]	5.51E + 10	6E + 11	
Configuration	Euro 5a 1.4 l spark ignition engine	Homologation limit	Remark
Emission	Measured value in WLTC	In NEDC	[–]
mCO_2 [g/km]	124.6	No limit	Vehicle homologated in NEDC (Euro 5a) → larger load collective in WLTC
mCO [mg/km]	366.2	1000	After treatment: 3-way catalyst, no GPF installed
mHC [mg/km]	36.2	100	High particle number concentration, very high particulate mass
mNO_x [mg/km]	36.6	60	
PM [mg/km]	14.4	5	
PN [#/km]	1.98E + 12	No limit	
Configuration	Euro 5a 1.6 l spark ignition engine	Homologation limit	Remark
Emission	Measured value in WLTC	In NEDC	[–]
mCO_2 [g/km]	137.0	No limit	Vehicle homologated in NEDC (Euro 5a), → larger load collective in WLTC
mCO [mg/km]	901.8	1000	After treatment: 3-way catalyst, no GPF installed
mHC [mg/km]	46.5	100	High particle number concentration
mNO_x [mg/km]	33.1	60	
PM [mg/km]	1.1	5	
PN [#/km]	1.91E + 12	No limit	
Configuration	Euro 5a 2.0 l diesel engine	Homologation limit	Remark
Emission	Measured value in WLTC	In NEDC	[–]
mCO_2 [g/km]	148.5	No limit	Vehicle homologated in NEDC (Euro 5a), → larger load collective in WLTC
mCO [mg/km]	88.0	500	After treatment: diesel oxidation catalyst, DPF
$mHC + mNO_x$ [mg/km]	226.7	230	NO_x-limit exceeded
mNO_x [mg/km]	215.0	180	
PM [mg/km]	0.6	5	
PN [#/km]	6.12E + 11	No limit	

to the NEDC. This vehicle was also included in the immission* measurements.

2.2 Particle immission* measurement

In this experiment, the engine exhaust gas was released into the test chamber and diluted by the internal air tumble, to reproduce a road side similar immission level. The concentration of NO_x and CO_2 were measured at the inlet and the

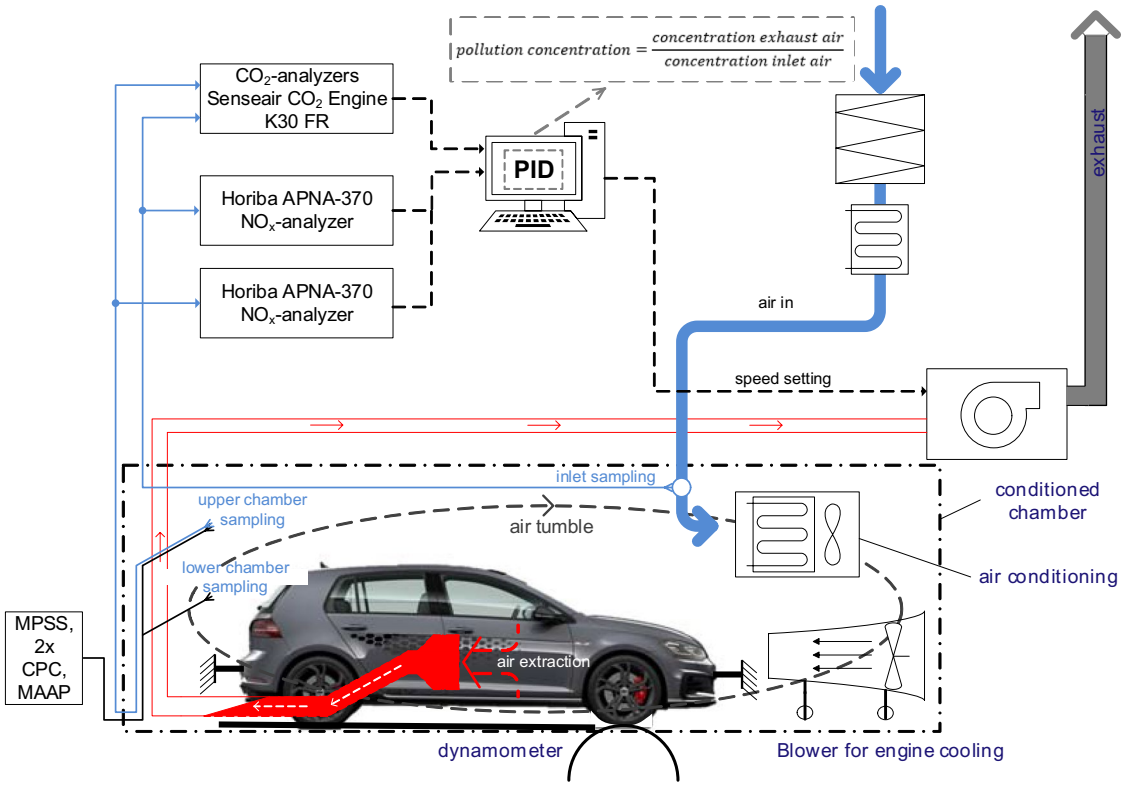

Fig. 2 Schematic illustration of the immission simulation, air extraction beside the vehicle, particle sampling lines behind the vehicle

outlet of the chamber to evaluate the pollution level in the test chamber. The pollution level was adjusted by regulation of the outlet chamber volume flow. Figure 2 shows the chamber outlet is located beside the vehicle to prevent a short circuit flow of the engine exhaust gas. The tumble motion in the chamber was forced by the conditioning system and the cooling air blower, which causes an excellent mixing of the exhaust gas within the test chamber. As evident in Fig. 2 the particle sampling lines are located quite near to the vehicle tailpipe. The chosen sampling positions serve a good tradeoff between a long mixing distance of the exhaust gas and a short extraction length (for low particle losses) of the particle sample flow. For this, the lower sampling line was almost at the same height as the exhaust pipe and about 1 m behind the car. The second sampling line was positioned at the same longitudinal position and at 1.76 m height. Both sampling lines were in line with the middle plane of the car and in the breakaway zone of the airstream around the vehicle. Thus a high intermixing can be expected even though the distance between the tailpipe and the sampling position was much closer than at roadside measurement stations. The installation regulations for the immission stations [2] specify the roadside location of the sampling inlets as follows: maximum 10 m away from the street, minimum 25 m away from the next high traffic crossing and at between 1 and 4 m height. The particles were sampled in the test chamber with a mobility particle size spectrometer (MPSS), two condensation particle counters (CPC) and a multi-angle absorption photometer for black carbon. The lower sampling line connects only to one CPC to evaluate the dilution with increasing distance to the exhaust pipe, whereas the second sampling line connects to all the other particle analyzers.

The MPSS is an in house development of TROPOS and detects the particle number size distribution in a range of 7–800 nm via 71 channels with a time resolution of 2.5–5 min. At first, the particles are charged with a bipolar diffusion charger. In a next step the charged particles are classified in an electrical field according to their electrical mobility which is inversely proportional to their sizes. Finally the size-resolved particles are counted by a CPC. The same model of MPSS is also used in the immission measurement stations “Dresden-Nord”, “Dresden-Winckelmannstraße” and “Leipzig-Mitte”, and the data from these stations were used for comparison in this study.

The single CPC counts the total particle concentration with a time resolution of 1 s. The inlet flow is saturated with butanol vapor. By cooling down the saturated aerosol, butanol condenses on the particles, which are growing to micrometer droplets. These are optically detectable.

The MAAP from Thermo Scientific has a time resolution of 60 s and measures the light absorption of particles which is then converted to black carbon mass concentration. It

detects the intensity of light with the wavelength of 637 nm (black carbon is the prime absorber) that is scattered back from the particles to calculate the amount of light absorbed by the particles loaded on the filter.

The extraction for the concentration of gases in the test chamber is located next to the particle extraction point behind the car at 1.76 m height. To analyze the NO_x concentration, two Horiba APNA-370 gas analyzers were used, which are also used in the environment measurement stations of the LfULG and have a minimum time resolution of 180 s. These instruments employ a chemiluminescence procedure and are able to measure parts per billion (ppb) through enrichment of the sample. To assess the CO_2-room concentration, non-dispersive infrared gas analyzers from Senseair were used, having a range from 0 to 5000 ppm and a time resolution of 0.5 s.

Additionally, a Horiba APNA CO_2 analyzer was installed during the measurement campaign at the immission station "Dresden-Nord", to establish a roadside reference value.

For the measurements the low and medium part of the WLTC were used, to represent an urban driving pattern including short accelerations, standstill times and a maximum velocity of 70 km/h. This driving profile was repeated four times to reach a stable pollution level in the chamber. Each experiment had a length of 4100 s and was performed at three different temperatures (0 °C, 15 °C, 30 °C), to include the temperature influence of different seasons.

3 Results

In Fig. 3, the particle concentration in the test chamber is compared to the concentration of the background measurement station "Dresden Winckelmannstraße" during the weekend from 25.10.2019 to 28.10.2019, to validate the background pollution load in the test chamber. "DD-Winckelmannstraße" was chosen for this comparison because the test chamber is located on the campus of the Technical University of Dresden, where immission levels rather represent the urban background as opposed to roadside concentrations (the next highly frequented streets are about 200 m away and shielded by buildings). During this test only the test chamber ventilation was active to transfer the outside air into the chamber. No other technical appliance was running in the test chamber. The particle size distribution in the measurement station is also detected by a MPSS of TROPOS.

Figure 3 shows that the total CPC (green) and the MPSS (red) concentration in the chamber are very similar to the particle number concentration at Winckelmannstrasse, which validates this measurement approach. The particle concentration in the chamber tended to be lower in comparison to the measurement station, but shows in general a similar behavior. This can be attributed to a particle loss in the intake system, which supposedly reduces the particle concentration within the chamber. Also, there is a time shift between Winckelmannstrasse and the chamber measurements. This originates firstly from the time for gaseous transport between Winckelmannstrasse and the chamber intake (app. 800 m) and the time to exchange the chamber volume sufficiently before a similar degree of contamination could be measured. Especially during night hours, both MPSS detected similar values. During heavy traffic phases, a higher deviation occurred due to the distance between the test chamber and the measurement station (about 800 m) including a large road crossing in the middle. Hence, the measurement station measured a higher or lower particle concentration depending on the wind direction and dilution. The summarized particle

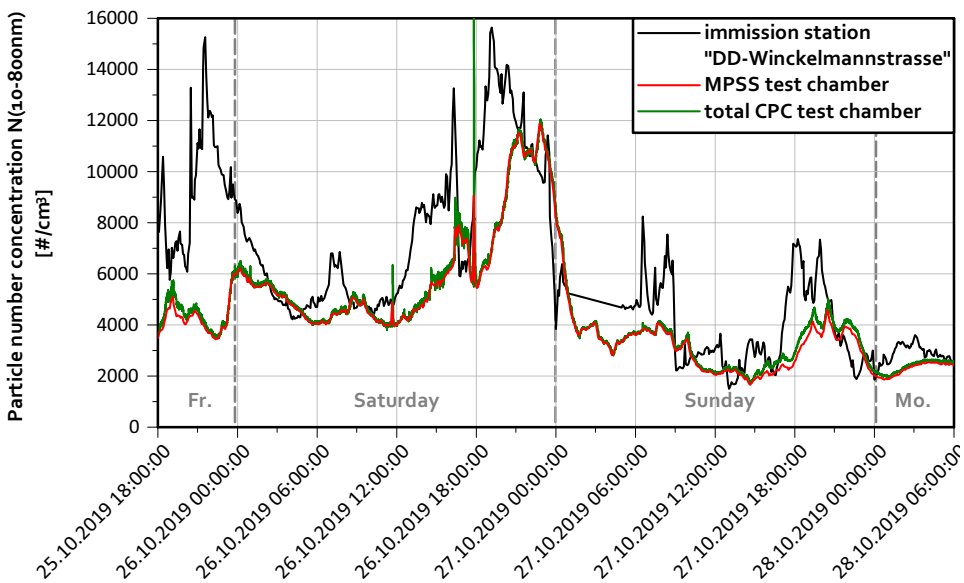

Fig. 3 PN measured in the test chamber compared to the values at the immission measurement station "DD Winckelmannstraße" for the weekend 25.10.2019–28.10.2019. This station is representative for urban background immission

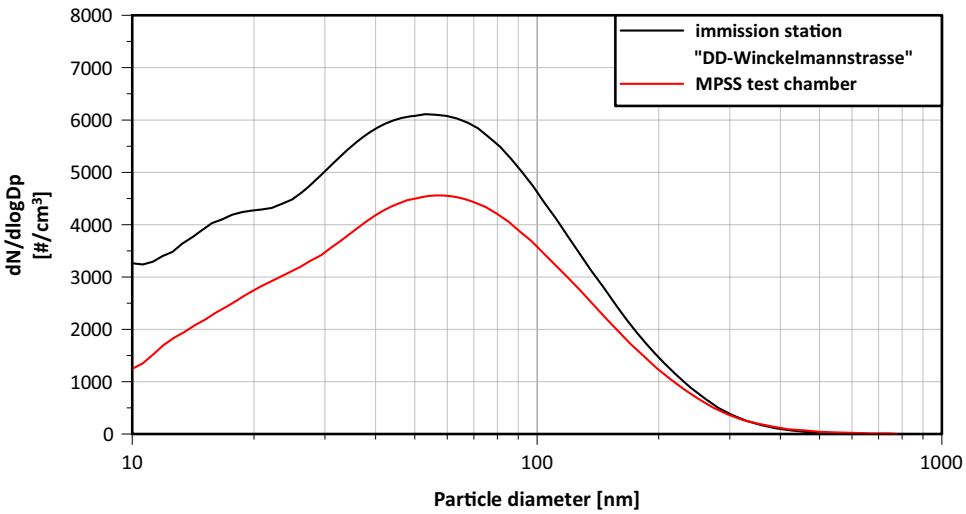

Fig. 4 Comparison of the average particle size distribution measured in the test chamber compared to the values at the immission measurement station "DD Winckelmannstraße" for the weekend 25.10.2019–28.10.2019. This station is representative for urban background immission

number concentration over all size classes (*N*: 10–800 nm) during that weekend at the immission station "Leipzig-Mitte" (heavy traffic) was about two times higher than in Dresden at "Winckelmannstraße" (quiet urban road / background). From this, it is derived that the basis value for particle pollution in the test chamber represents a background immission station. In Fig. 4, the mean particle size distribution of that weekend is shown. The size distribution in the chamber agrees well with that of the measurement station with maximum at about 50 nm. The reduced particle concentration in the test chamber can be explained with the particle loss in the chamber inlet and inside the test chamber. Unfortunately, this could not be assessed properly, because there was no particle measurement device installed at the inlet. A base load of 2 µg/m^3 of black carbon was detected with the MAAP. In summary, satisfactory agreement was established of the base particle concentration in the test chamber compared to the urban background measured at the station "Winckelmannstraße".

During the WLTC emission measurements (Fig. 1), a high amount (up to 20 µg/m^3) of soot inside the test chamber was detected by the MAAP, even though the exhaust gas was completely extracted out of the chamber into the CVS emissions measurement system. To elucidate this phenomenon, black carbon was measured during the startup of the test bench (Fig. 5).

Two black carbon monitoring devices MICROAETH AE51 (SN 821, SN 829) were installed. One was positioned behind the car and one in the dynamometer pit next to the electric machine. The test bed systems were initialized as follows: at first, just the air conditioning system and the scavenging ventilation for the induction of outside air were activated. Then, the dynamometer controls were activated, but without the rollers moving. Both systems had no influence on the base soot concentration of about 1 µg/m^3. Then,

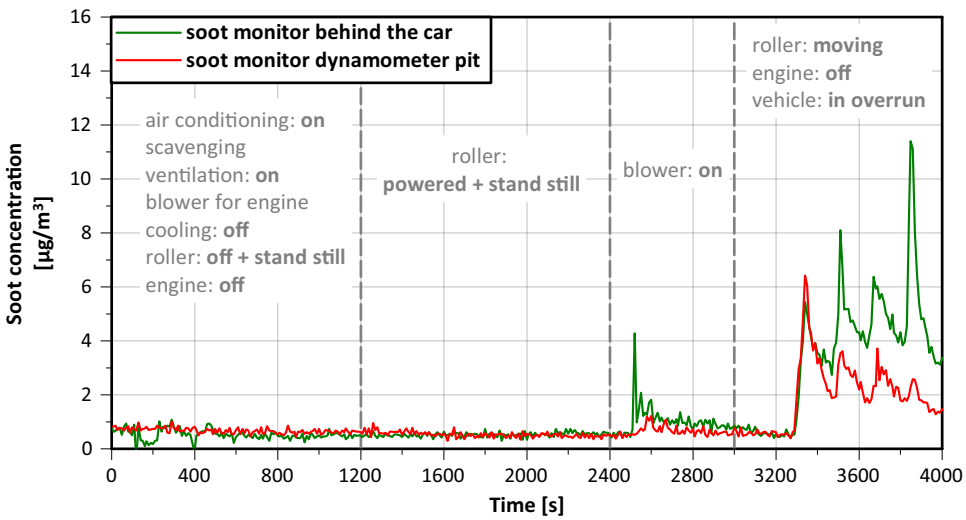

Fig. 5 Evaluation of the test bench system. Does any part of the measurement chain have an influence on the soot concentration? Vehicle only in overrun, i.e., not moving actively

the air stream blower for the engine cooling was started, which produced a soot peak which decreased within a few minutes. It is supposed that the blower stirred up some dust and particles, which then settled elsewhere. In the next step, the chassis roller was accelerated and decelerated up to 130 km/h for four times. The vehicle was motored, i.e., the engine was not powered up. This procedure produced a speed or acceleration dependent rise in soot concentration. It must be concluded, that tire wear was the source of the black carbon emission and immission*, respectively. Also, the maximum concentration increased with every acceleration from 6 to 11 µg/m^3, which implies that there is a correlation to the tire temperature. This is backed up by the information of Ref. [4]. In a second experiment, a WLTC was run without vehicle on the roller, to verify the rotating e-machine as one possible source of soot. No rise in soot concentration was detected.

Figure 6 shows the soot measurement during a WLTC, with the car engine actively driving chassis rollers. The exhaust gas was completely extracted from the chamber. From this, a direct correlation of the soot concentration with the transmitted power between the tire and the dynamometer was determined. Moreover, high peaks during active deceleration/braking also occurred, which presumably can be assigned not only to tire but additionally to brake wear. The soot concentration stagnated during the first 10 min of the cycle, i.e., during low power city driving, which confirms the temperature and transferred power dependence of tire wear. The black carbon concentration in the dynamometer pit showed a similar behavior as behind the car, albeit at lower level, due to the shielding of the floor panels. In conclusion, a significant black carbon concentration was detected, which did not originate from the combustion engine. This is an important finding and needed to be considered in the following evaluation of the immission simulation experiment.

Figure 7 shows the immission simulation, i.e., the vehicle exhaust gas was released into the test chamber. Shown in the first row is the applied velocity profile, consisting of the succeeding section of WLTC low and medium, repeated four times. The nitrogen oxide concentration at the chamber in- and outlet, shown in the second row, did not show an obvious dependency on the load collective. The influence of the NO_x taken in with the ambient air apparently exceeded the NO_x concentration emitted by the vehicle (see, e.g., concentration steps at 1750 s and 2500 s compared to, e.g., 2000 s). Also, the NO_x concentration in the chamber was extremely low (see *y*-axis to the right!). Hence, the NO_x concentration was not deemed suitable to indicate the pollution level in the test chamber. In contrast, the carbon dioxide concentration was settled after about 500 s at 800–900 ppm. This level was also dependent on the ambient intake CO_2 level. For the calculation of the "pollution level" the outlet CO_2 concentration was divided by the inlet CO_2 concentration. The pollution level in the chamber was always between 1.2 and 1.8 depending on the tested car, i.e., the CO_2 emission.

Figures 7 and 8 show the carbon dioxide level measured at the immission station "Dresden-Nord" for the week from 21.10.2019 to 28.10.2019 (Monday–Monday), with maxima at about 600 ppm. At night and on the weekend the carbon dioxide level approached the global environment level of about 410 ppm. Also shown is the wind speed during that

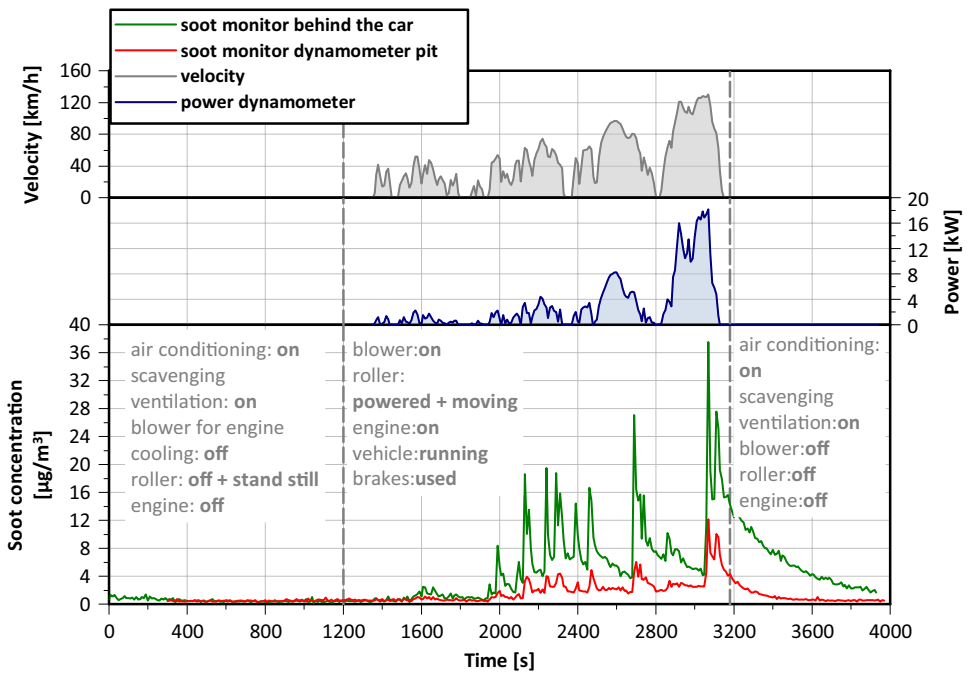

Fig. 6 Investigation of the soot concentration during a WLTC. The vehicle was actively driving the chassis roll. Exhaust gas was extracted completely into the CVS tunnel, i.e., there was no exhaust gas in the test chamber

week. The reduction in CO_2 concentration towards the end of the week correlates well with the increase in wind speed, i.e., with the higher dilution. The pollution level in the test chamber was about 33% higher than roadside at "Dresden-Nord", which indicates that the "immission* atmosphere" in the test chamber was similar to that at "Dresden-Nord".

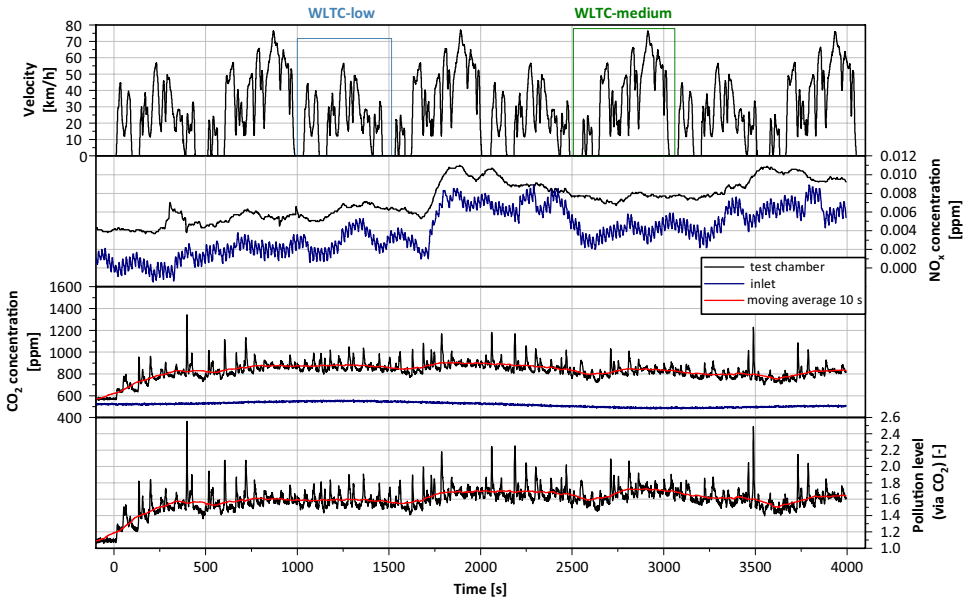

Fig. 7 Pollution levels during the immission simulation cycles, four sequences each of "WLTC low" followed by "WLTC medium". NO_x concentration fluctuated independently from the driving cycles, probably due to external effects. Also the NO_x concentration was extremely low, in the ppb range! CO_2 was a very reliable indicator for test chamber dilution, with concentrations of several 100 ppm

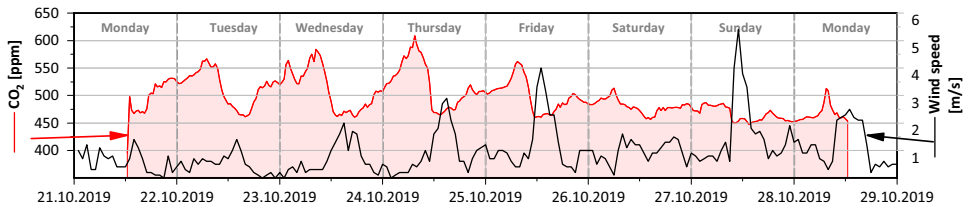

Fig. 8 CO_2 concentration and wind speed during one week at the roadside immission station "Dresden-Nord" (intermediate traffic hot spot) CO_2 is normally not measured in these stations

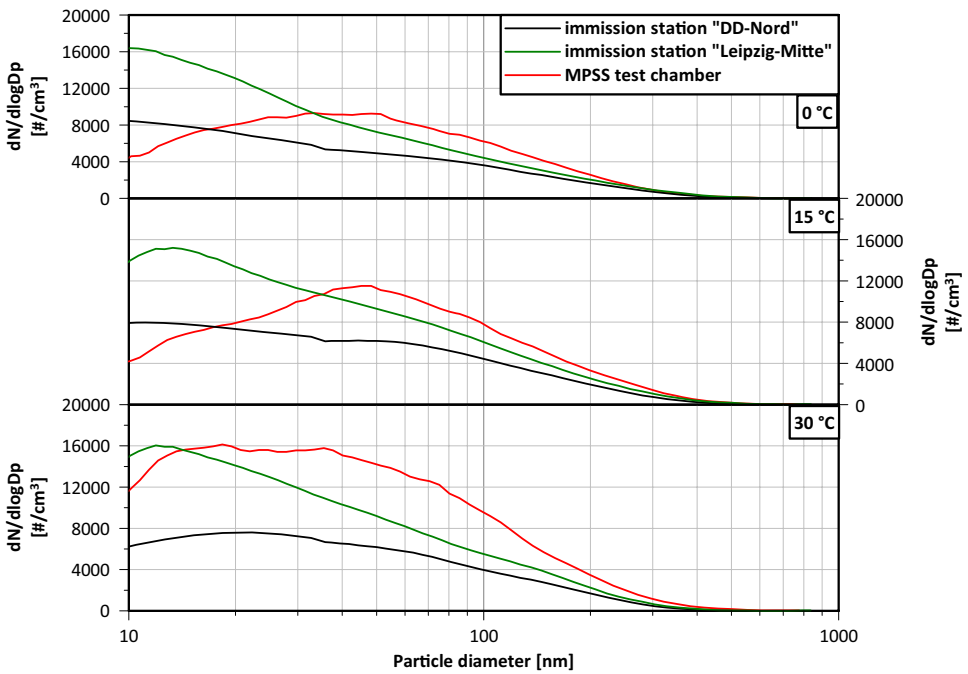

Fig. 9 Particle size distribution, average of all measured vehicles (red) compared to the immission station "Dresden-Nord" (black) and "Leipzig-Mitte" (green) at 0 °C (top), 15 °C (middle) and 30 °C (bottom). The peak diameters do agree with literature data for tire and brake particles. Detection at roadside stations is subject to weather conditions and therefore far lower than in the forced convection of the test chamber. The general level of the particulate concentration is represented very well in the environment simulation in the test chamber

In Fig. 9, the average chamber particle size distribution of all tested cars (red) is compared to data from the measurement stations “Dresden-Nord” (black) and “Leipzig-Mitte” (green). The selected roadside data show the average course from December to February 2018 for 0 °C, September to November 2018 for 15 °C and July to August for 30 °C. The traffic density for “Leipzig-Mitte” was about 42,000 vehicles per day and for “Dresden-Nord” about 14,200 vehicles per day in that time. The particle measurement devices in the stations are the same as in the current experiment and are also supervised by TROPOS. The higher traffic volume in “Leipzig-Mitte” is also reflected in the higher particle concentration compared to “Dresden-Nord”. The total particle concentration in the test chamber rose with increasing temperature and more small particles between 10 and 40 nm were detected. This behavior was not evident in the roadside data. There, nearly no influence of the temperature on the particle size distribution was detected. During the chamber tests at 0 °C and 15 °C the particle concentrations smaller 50 nm were significantly lower than at the station. This can possibly be traced to the formation of ultrafine particles, UFP, in the ambient. These are formed out of the gas phase during photochemical processes and depend on environmental effects (e.g., UV radiation) [7]. Consequently this share of UFP is missing in the chamber tests. Above 50 nm, the particle concentration in the chamber tends to be higher than at the roadside. A direct carry-over to the road side data is currently not possible. There, tire, brake and exhaust emissions exist simultaneously and cannot easily be separated [4]. However, the similarity in roadside immission and test chamber immission* indicates that the measurements qualitatively represent real-world emission reasonably well. A better quantification and comparison is future work, since this requires a much higher effort in measurement equipment and analysis. As described in Ref. [4] brake and tire wear can cause high particle concentration emission (< 150,000 #/cm^3) in size ranges from 40 to 80 nm depending on the driving situation. Extreme situations like emergency braking with high brake temperatures can cause high particle concentrations in the small size ranges with a peak at 10 nm. Hence, a higher influence of brake and tire wear in the small particle size ranges can be assumable for increasing ambient temperatures. Nevertheless, there is a higher pollution level in the chamber than at the roadside, as shown in Fig. 8. The particle emission from tires and brakes obviously cannot be diluted in the test chamber quite as much as at the roadside. The flow pattern in the chamber apparently forces the transfer of these particles to the sampling point. On the road only about 10% of tire and brake particles become airborne and their concentration is subject to local weather condition [4]. Another reason for low particulate counts is the relatively large distance between the origin of the emission (tires and brakes) and the immission sampling point. Therefore, brake and tire particles contribute much less to the total particulate immission detected by roadside stations compared to the immission simulation test chamber. Also, higher tire wear can be assumed on the roller dynamometer because of the very rough roller surface.

Figure 10 shows the mass concentration of black carbon in the test chamber for the test vehicles, as well as the roadside measurements from “Dresden-Nord” (medium traffic hot spot) and “Winckelmannstraße” (urban background). From these data, the vehicles can clearly be classified in the groups “with particle filter” and “without particle filter”, irrespective of the homologation in Euro 5 or Euro 6. The red and green dashed lines represent the average soot levels of the two groups. Also, a rising soot mass concentration with increasing chamber temperature was observed. Especially, the data of the Euro 6 homologated vehicles with the lowest combustion originated particle emission were more dependent on ambient temperature. This confirms the assumption that the measured tire and brake originated

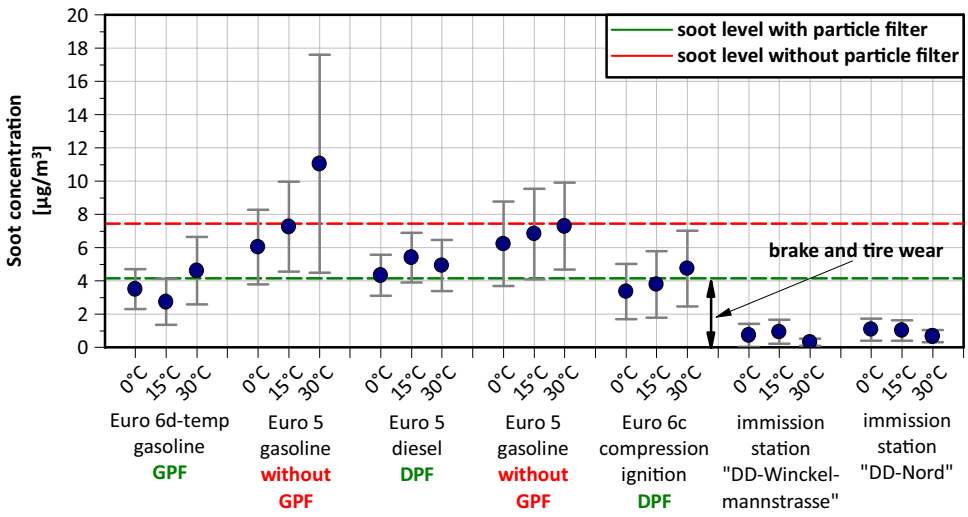

Fig. 10 Mean soot concentrations for the immission simulation in the test chamber in comparison with the immission stations “DD-Winckelmannstraße” and “DD-Nord”

particle concentration was a function of chamber temperature. As verified in the initial engine emission measurement (Table 1), the tested cars with particle filter emitted almost no particle mass. Assuming that the brake and tire wear of every car was similar in a similar test load collective, a black carbon level caused by brake and tire wear can be defined at 4 µg/m^3. Accounting also for the 33% higher pollution level in the chamber compared to roadside measurements (Fig. 7), the mean overall soot mass of the vehicles without particle filter of about 7 µg/m^3 (air in the chamber) can be corrected to an average engine soot mass of 2 µg/m^3 ((7–4 µg/m^3)·(1–0.33) ≈ 2 µg/m^3). The remaining difference of about 1 µg/m^3 compared to the immission stations can be attributed to the environmental effects missing in the chamber, like variable dilution/wind, UV radiation, variable emissions from traffic/driving situations and other particle sources (sand, other road dust).

4 Conclusion

In the research presented in this paper, a method was developed to simulate urban road particle immission in a test chamber. For this, five passenger cars with various engines and exhaust after treatment systems were tested in a roller dynamometer test chamber with an adjustable ventilation system, at three different chamber temperatures, to represent different seasons. Initially all vehicles were successfully checked with respect to their (correct) exhaust emission behavior in a WLTC by means of a constant volume sampler, CVS, exhaust analysis system. In the succeeding immission* tests, the exhaust gas was released into the test chamber and diluted and mixed with induced ambient air in the test chamber circulation flow pattern.

The measured and corrected particle number and black carbon mass concentrations agreed well with the measured roadside values. In the test chamber a strong influence of tire and break temperature on their respective emissions was found, which corresponds to the findings in literature. This dependency largely was not detected at roadside immission measurement stations because a direct correlation with braking or acceleration of individual vehicles is not possible and only summary effects can be measured. Also, environmental fluctuations, in particular dilution through convection (wind conditions) do not allow for a direct measurement of such effects. This is one of the purposes of the immission* simulation in the test cell.

The results show that direct injection spark ignition engines without particle filter can cause a significant particle concentration. The increasing particle emission from the increasing number of DI-Otto-engines, in a long-term consideration, is at least partly compensated for by the introduction of vehicles equipped with particle filters, in particular Diesel vehicles, since the introduction of Euro 5 in 2009.

In general, the developed method is well suitable to study the road similar immission caused by various traffic situations.

To entirely elucidate the context between engine particulate emission and environmental immission, some improvements and extensions can be concluded from the current work. These include the detection of the ambient particle concentration at the chamber inlet, collection of additional roadside CO_2 immission data, introduction of a more intensive chamber ventilation and improved control system, CFD simulation of the flow pattern, emission concentration and time-dependent dilution in the chamber, direct sampling of tire and brake wear emission at the source for correlation with the immission data, extension of the measurement data base, simulation of various environmental effects in experiment and CFD.

One important conclusion from the current work is, that the vehicle emission homologation needs to be reconsidered. Monitoring the exhaust emission alone cannot capture the entire vehicle emission, other sources like tire and brake wear need to be considered. From this perspective also so-called “zero emission vehicles” like battery electric vehicle and fuel cell cars must be evaluated considering their overall particle emission. For such evaluations, closely controlled test methods and conditions are necessary to produce robust and repeatable results. The developed method is a reliable and expedient procedure for these tests.

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Data availability Weinhold K.; Wiedensohler A.; Dobberkau M.; Atzler F.: “Partikel in PKW-Emission und Immission”. Final report of the LfULG 2020, https://publikationen.sachsen.de/bdb/artikel/36768q.

Code availability Not applicable.

Declarations

Conflict of interest On behalf of all authors, the corresponding author declares that there is no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Consent TROPOS and LfULG.

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