Reduction Trends of Particle Number Traffic Emissions and Modelled Concentrations in a Typical Street Canyon in Germany

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Introduction

For particulate matter, besides particle mass (PM), also other characteristics are currently discussed regarding the assessment of air quality. For Euro-5 Diesel and Euro-6 Gasoline vehicles, additionally to PM, much more demanding particle number (PN) emission limits have been implemented in European legislation (European Commission, 2012). Note that in this emission legislation, particle number (PN) refers to the number of solid particles (i.e. after thermal treatment).

In the vicinity of a street, PN concentrations are dominated by road traffic sources. Due to the introduction of particle filter technology in Diesel vehicles, a large reduction of soot particles is to be expected in that segment. Compared to that, the contribution of direct injection gasoline vehicles to PN will grow. In addition to primary exhaust particles, secondary particles generated by nucleation of low-volatile components in the exhaust gas contribute to PN.

Model

Box model calculations of particle number (PN) concentrations in a typical street canyon with high traffic volume in Germany for the years 2010, 2015, 2020, 2025 and for a scenario “electric mobility” (electric vehicles only) were done by coupling an aerosol model (MADE, Ackermann et al., 1998) and a gas-phase chemistry model (Memmesheimer et al., 2007). In MADE (Modal Aerosol Dynamics Model for Europe), particles are distributed to three modes (nucleation mode (nuc), accumulation mode (acc) and coarse particles). For each mode, a lognormal distribution with respect to particle size is assumed. Since the contributions of coarse particles to PN are negligible, coarse mode is not used here.

Emission, nucleation and aerosol aging processes are accounted for. Dilution is parameterised by a simple two-stage process. The model street is no real street but generic, typical with respect to traffic volume and building geometry.

Input data

As input data, hourly values of meteorological parameters, background PN concentrations and vehicle emissions are needed. For urban background, we used continuous measurements of PN and soot at Leipzig-TROPOS (urban background) done by Rasch, F., et al. (2013).

Traffic volume in the model street is based on Corneliusstraße in Düsseldorf, because this is a typical urban main road and a street canyon with high traffic volume and concentration levels in the range of the limit value for NO_2. The annual average daily traffic (AADT) and its distribution to passenger cars (PC), light duty vehicles (LDV), powered two-wheelers (PTW) and heavy duty vehicles (HDV) used for the model street are shown in Table 1.

Table 1: Annual average daily traffic (AADT) and distribution to vehicle types for the model street

	PC	LDV	PTW	HDV	AADT
veh./24h	42.504	2.310	462	924	46.200
fraction	92%	5%	1%	2%	100%

For each vehicle type and year, the mean fleet composition in Germany was used as given by HBEFA3.1 (Handbook of Emission Factors, version 3.1, www.hbefa.net). It is shown in Figure 1. According to legislation, introduction of Euro-6 vehicles was assumed to be a two-step process, which was not accounted for in HBEFA3.1 yet. All Euro 6 gasoline vehicles were assumed to be direct injection vehicles.

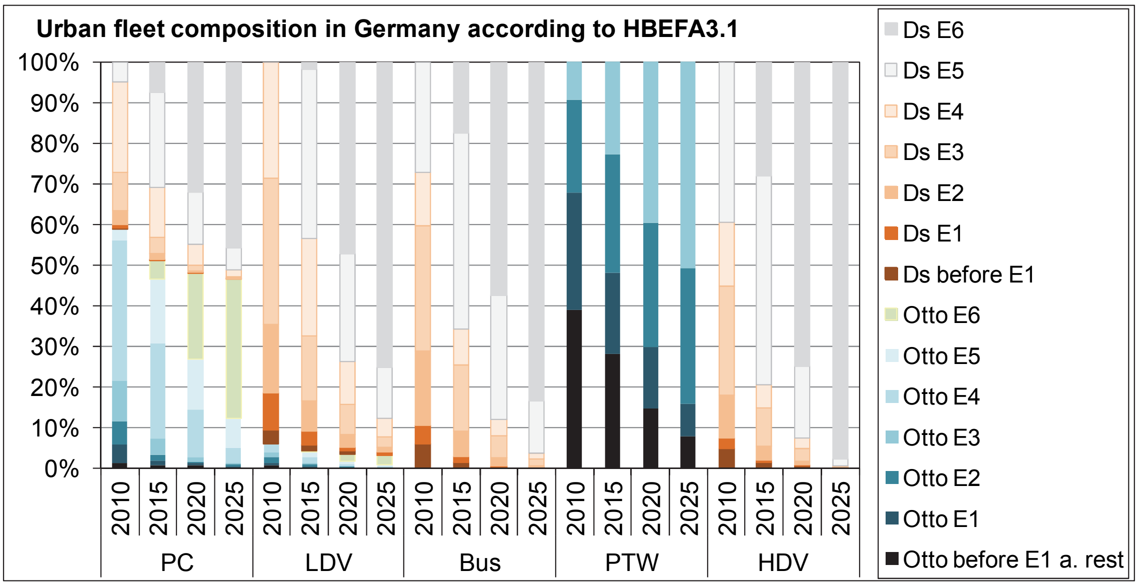

Figure 1: Urban fleet composition in Germany in 2010 and projections up to 2025 for passenger cars (PC), light duty vehicles (LDV), Busses, powered two-wheelers (PTW) and heavy duty vehicles without busses (HDV), according to HBEFA3.1

The resulting PN emissions are shown in Figure 2. For the scenario “electric mobility”, tailpipe emissions are set to zero, while particle emissions by abrasion processes and resuspension remain unchanged. The latter contribute only little to PN.

Annual mean values of tailpipe PN emissions in 2025 are reduced by 90% compared with 2010 due to a high fraction of Euro-6 vehicles in the fleet.

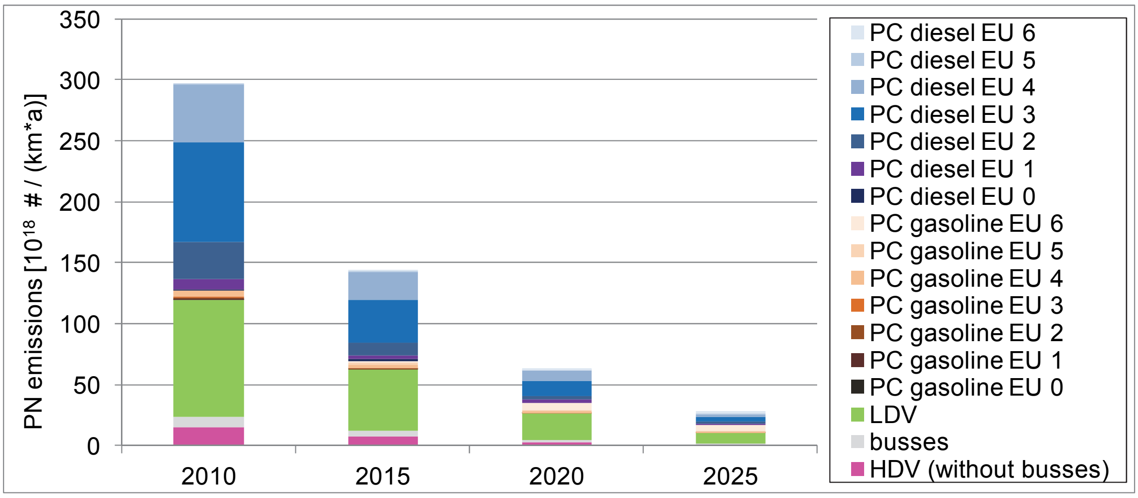

Figure 2: PN tailpipe emissions (non-volatile) for the typical street canyon in Germany 2010 to 2025

Results

Using the model and its input parameters and boundary conditions described above, air quality calculations were done for 2010 (base year), 2015, 2020, 2025 (forecast years) and for the scenario “electric mobility”.

Base year

For the base year, we found the following:

- The modelled annual mean value for the “typical” street canyon 2010 amounts to 22×10^3 #/cm^3. This lies within the range of urban measurement campaigns given in literature, see e.g. the HEI report 2013 (11×10^3 #/cm^3 up to 48×10^3 #/cm^3).

- We compared the model calculation with the annual mean value of 2010 of measurements at Eisenbahnstraße in Leipzig (20×10^3 #/cm^3), which is a traffic influenced measurement station in a street canyon near the urban background station we used (TROPOS). The annual mean of the model exceeds that of the measurements at Eisenbahnstraße by 2×10^3 #/cm^3. This is in line with expectations, since the "typical" high traffic volume (46,200 vehicles per day) exceeds that at Eisenbahnstraße (11,000 vehicles per day).
- The modelled annual mean value of 2010, if emissions are switched off, amounts to 12×10^3 #/cm^3. This complies well with the annual mean value measured at TROPOS, which was used as a boundary condition for the model.
- If aerosol dynamics is switched off, the model underestimates PN by 23%. This shows that, in the vicinity of the street, nucleation is the dominant process of aerosol dynamics.

In Figure 3 (top), the annual mean diurnal variation of PN is shown

- for the modelled typical street canyon,
- for a model calculation where emissions were switched off,
- for the measurements at TROPOS and
- for the measurements at Eisenbahnstraße.

For comparison, the annual mean diurnal variation of the PN vehicle emissions is shown below.

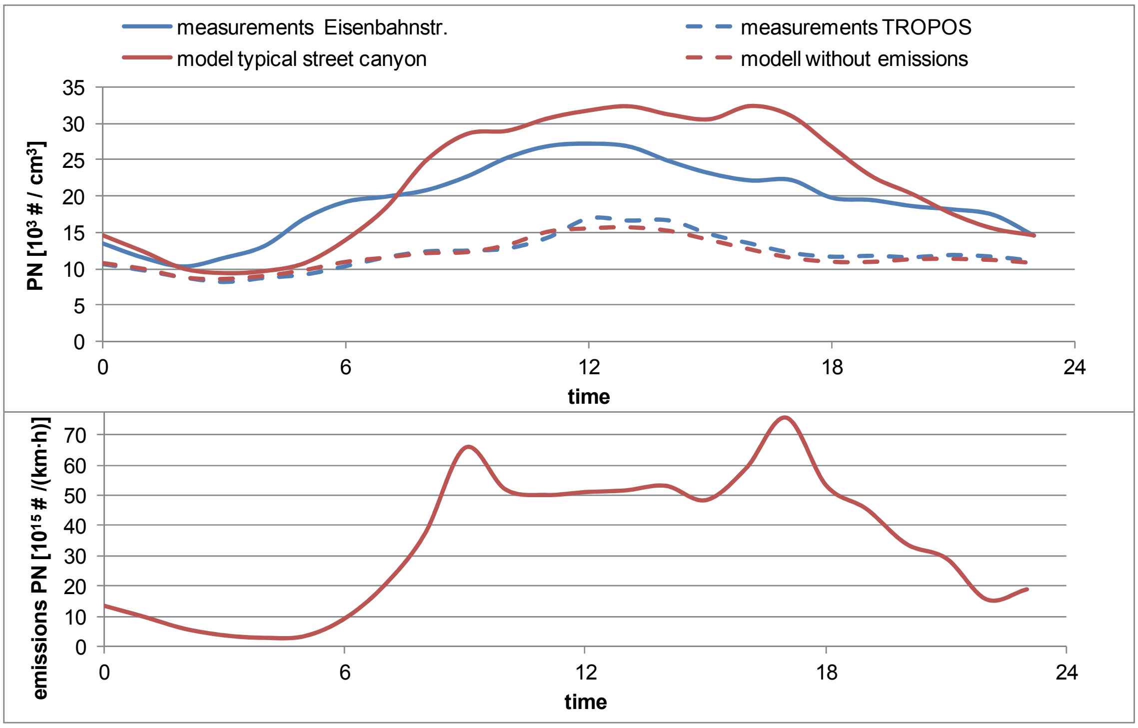

Figure 3: Annual mean diurnal variation 2010 of measured (Leipzig-Eisenbahnstraße and Leipzig-TROPOS) and modelled ("typical" street canyon with and without emissions) PN concentrations (top) and of emissions (bottom)

The following can be seen:

- Between 7:00 a.m. and 9:00 p.m., PN model calculations for the typical street canyon exceed measurements taken at Eisenbahnstraße. Similarly to the annual mean values, this is caused by a higher traffic volume.
- In the model, there are PN maxima at the peaks of traffic volume at 09:00 a.m. and 05:00 p.m. and there is also a maximum caused by photochemistry at noon. In the measurements at Eisenbahnstraße, the morning maximum already occurs at 06:00 a.m.. One explanation for this are earlier working hours in Saxony compared with North-Rhine Westphalia.
- If emissions are switched off, the model reproduces the annual mean variation in urban background (measurements TROPOS) well.

Forecast years

Modelled annual mean PN concentrations in the typical street canyon for the forecasted years and the scenario “electric mobility” are shown in Figure 4.

Within the time frame of 2010 to 2025, PN concentrations are expected to be reduced by about 30%. Apart from contributions of urban background air, this lower reduction compared with the direct emission reduction (-90%) is due to the formation of secondary particles by nucleating gas-phase exhaust components (sulphuric acid and low volatile organic compounds). In the “electric mobility” scenario, there are no tailpipe emissions, and PN concentration is reduced by 60% compared with 2010.

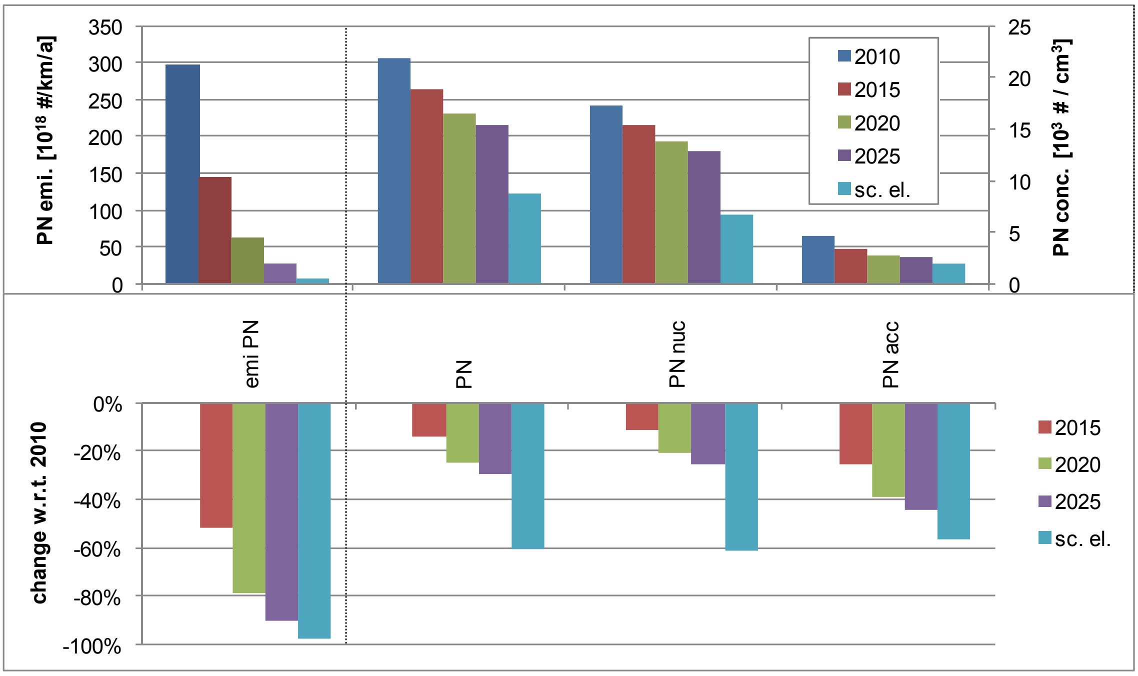

Figure 4: Annual mean values of emissions and model calculations in the typical street canyon for PN (total, nucleation (nuc) and accumulation (acc) mode) and relative changes with respect to base year 2010

Contributions to PN

The contributions of the various source processes to PN concentrations in the street canyon were estimated as follows:

- The contribution of the background is known from the measurements.
- To estimate the contribution of secondary particles, a model calculation without aerosol dynamics was done. The difference to the standard calculation was attributed to secondary particles. This is only an approximation: Due to the nonlinearity of the model, the results from differing model runs cannot be simply added or subtracted. Therefore, the partitioning derived here is to be taken as a rough estimation.
- The contribution of resuspension and abrasion to PN may be neglected: Abrasion and especially resuspension particles are large in comparison with soot or nucleation particles and contribute strongly to particle mass but hardly to PN.
- The remaining particles come from primary exhaust emissions and can be distributed to the vehicle types according to their emissions.

The resulting partitioning of modelled PN to its contributing sources is shown in Figure 5.

The contribution of background particles to PN in the model street increases from 55% in 2010 to 66% in 2025, the contribution of secondary particles slightly decreases from 21% to 18% and the contribution of directly emitted particles decreases from 24% to 16%. Also shown in Figure 5 is the partitioning of these primary particles to vehicle types.

Especially for PC, contribution changes can be observed: In 2010, Diesel PC contribute about 14% to PN concentration, which is reduced to about 6% in 2025. This is caused by the propagation of particle filter technology in Diesel vehicles within the fleet and also of vehicles obeying the stricter Euro 6 norm. At the same time, the contribution of gasoline PC increases from less than 1% in 2010 to about 4% in 2025, mainly due to the contribution of direct injection gasoline vehicles to PN.

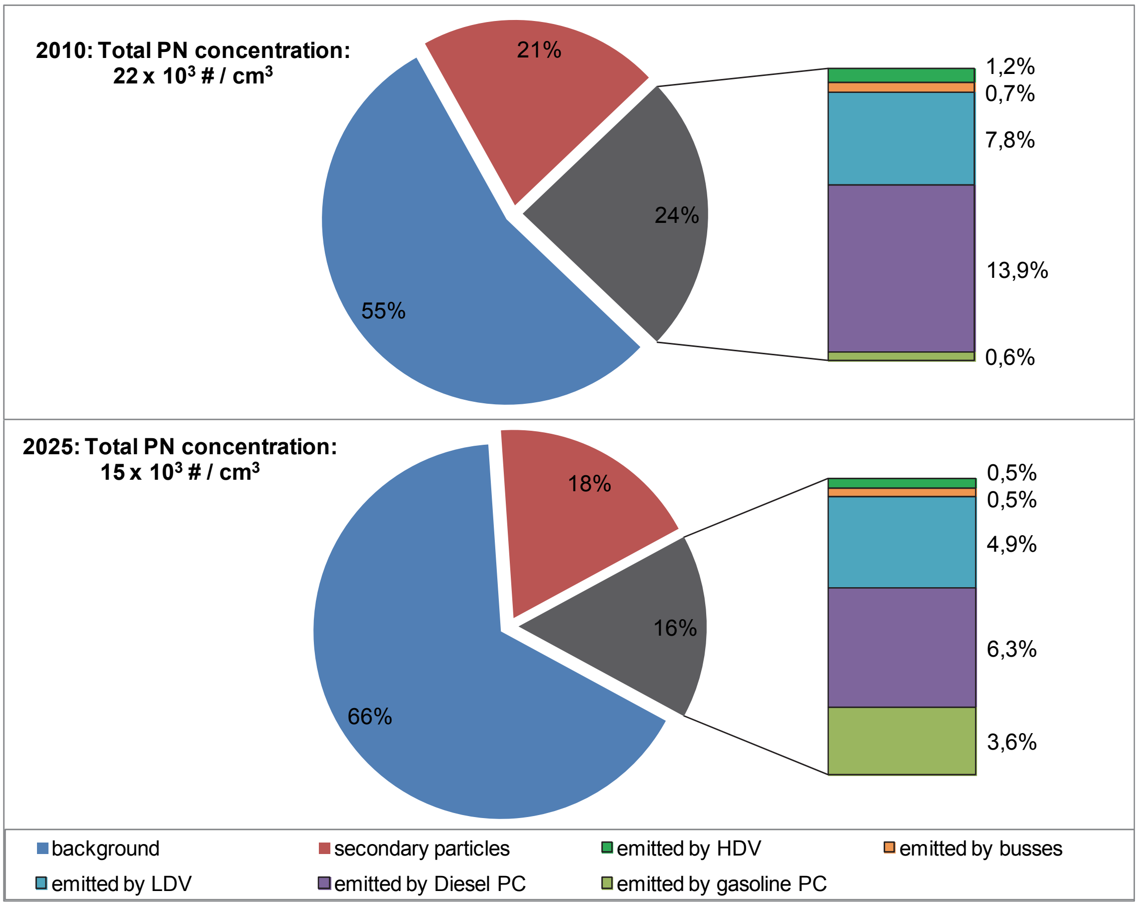

Figure 5: Contributions to PN in the street canyon in 2010 and 2025: background, secondary and primary particles (distinguished by emitting vehicle type)

Discussion

Based on HBEFA3.1 and current legislation, PN emissions (solid) are forecasted to be reduced significantly (-90% between 2010 and 2025). Modelled PN concentrations are reduced less in that period (-30%), due to contributions of the background and the formation of secondary particles from nucleating gas-phase compounds in the exhaust. The contribution of direct (solid) emissions to PN concentration in the street canyon decreases from 24% to 16% between 2010 and 2025. The contribution of gasoline PC emissions to PN concentration in 2025 amounts to 3.6%, mostly from Euro 6 direct injection vehicles.

These results show that it is reasonable to distinguish between primary particles (non-volatile, direct exhaust emissions) and secondary particles (volatile, generated by secondary particle formation, both in background air and in the street canyon). The latter are small (D ~ 10 nm), consist of sulphuric acid and low-volatile OC, and considerably contribute to PN. Given the large contribution of volatile particles to PN, it appears important also in air quality, or potentially health effects studies, to treat volatile particles separately from non-volatile particles.

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