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Exhaust particle and NO_x emission performance of an SCR heavy duty truck operating in real-world conditions

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HIGHLIGHTS

- Three different emission factor calculation methods were compared.
- Nucleation particles dominated in particle number emissions of SCR truck.
- Heavy driving conditions increased both NOx and particle number emission factors.
- Average real world NOx emissions were close to EURO IV emission limit value.

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ABSTRACT

Particle and NO_x emissions of an SCR equipped HDD truck were studied in real-world driving conditions using the "Sniffer" mobile laboratory. Real-time CO_2 measurement enables emission factor calculation for NO_x and particles. In this study, we compared three different emission factor calculation methods and characterised their suitability for real-world chasing experiments. The particle number emission was bimodal and dominated by the nucleation mode particles (diameter below 23 nm) having emission factor up to 1×10^{15} #/kg_{fuel} whereas emission factor for soot (diameter above 23 nm that is consistent with the PMP standard) was typically 1×10^{14} #/kg_{fuel}. The effect of thermodenuder on the exhaust particles indicated that the nucleation particles consisted mainly of volatile compounds, but sometimes there also existed a non-volatile core. The nucleation mode particles are not controlled by current regulations in Europe. However, these particles consistently form under atmospheric dilution in the plume of the truck and constitute a health risk for the human population that is exposed to those. Average NO_x emission was 3.55 g/kWh during the test, whereas the Euro IV emission limit over transient testing is 3.5 g NO_x/kWh. The on-road emission performance of the vehicle was very close to the expected levels, confirming the successful operation of the SCR system of the tested vehicle. Heavy driving conditions such as uphill driving increased both the NO_x and particle number emission factors whereas the emission factor for soot particle number remains rather constant.

1. Introduction

Road traffic produces particulate and gaseous pollutants in the vicinity of people, leading to frequent exposure to high concentrations of toxic species, which negatively affect human health (HEI, 2010). Particulate pollutants, expressed either by the mass of particulate matter (PM) or the particle number (PN), together with nitrogen oxides (NO_x) are the two pollutants of primary concern. Elevated ambient PM concentrations have been linked with cardiovascular and respiratory diseases that lead to increased morbidity and even mortality (e.g. Hoek et al., 2013). NO_x, and in particular NO_2, are long known to cause adverse respiratory effects, which increase in severity for people with asthma (Frampton and Greaves, 2009). Silva et al. (2013) estimated that 470,000

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premature deaths are associated with anthropogenic ozone and 2.1 million deaths with anthropogenic PM annually on a global level.

Diesel combustion has historically shown to be the main source of PM in roads. Diesel exhaust PM consists of carbonaceous soot, metal compounds mainly originating from lubricant oil, and semi-volatile organic and sulphuric compounds (e.g. Heywood, 1989; Tobias et al., 2001). The size range of diesel particles comprises a soot mode (frequently called as accumulation mode) and a nucleation mode, with a considered boundary between the two modes at the 20–40 nm range. The soot mode particles typically dominate the emitted particle mass whereas the nucleation mode frequently dominates the particle number concentrations (Kittelson, 1998; Maricq, 2007). Several studies show that a core for nucleation mode particles initially forms during combustion (Rönkkö et al., 2007; Filippo and Maricq, 2008: Lähde et al., 2010), their number decreases in the tailpipe (Heikkilä et al., 2009), and after that, they increase again during cooling and dilution of exhaust in the atmosphere. A different pathway for nucleation mode formation is due to sulphuric components nucleation (Shi and Harrison, 1999; Lemmetty et al., 2007; Arnold et al., 2012; Rönkkö et al., 2013).

Heavy duty diesel (HDD) trucks have been reported to significantly contribute to PM and NO_x emissions. A collection of different studies by ICCT (2013) shows that HDD trucks contribute to more than 40% of total PM and NO_x emissions in highways around the world, despite they represent only 1–4% of the total fleet of road vehicles. For this reason, regulations in Europe and elsewhere try to reduce exhaust emissions from HDD trucks. In Europe, latest emission standards at a Euro VI level require 0.01 g PM/kWh and 0.46 g NO_x/kWh over transient testing (Dieselnet). Such levels are only reached by a combination of Diesel Particulate Filter (DPF) for PM control and several NO_x reduction technologies, including Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR). The SCR device operates by catalytically reducing NO_x with ammonia (NH_3) over a catalyst surface. NH_3 is added to the exhaust by means of water solution of urea injection upstream of the SCR catalyst in the tailpipe (Amanatidis et al., 2014). Typical SCR devices for on road vehicles can achieve NOx reduction efficiencies in excess of 80% (Chi, 2009).

Because of its high efficiency, the SCR system has been also used in earlier HDD trucks, including Euro IV and Euro V ones, which represent the majority of trucks in European roads today. For example, some 60% of the total HDD fleet operating in Germany in 2014 belonged to the Euro V technology, according to TREMOD (2012). Euro V NO_x limits have been primarily reached with SCR but without DPF for PM control. In such a configuration, the SCR operation may lead to an increase in particle emissions. The modelling study by Lemmetty et al. (2007) proposed that the SCR system, basically the emission of ammonia, could enhance the nucleation particle formation during the cooling and dilution process of the exhaust. The experimental study by Thiruvengadam et al. (2012) supported this hypothesis; they observed that under high exhaust temperature conditions the urea injection into the SCR system increased the nucleation mode particle emission of a HDD vehicle by even an order of magnitude. Also Guo et al. (2014) reported that SCR equipped vehicles seem to emit nucleation particles. However, under low exhaust temperature conditions, Karjalainen et al. (2012) did not observe particle generation caused by the SCR system. The SCR systems may even increase the emission of solid nanoparticles (Amanatidis et al., 2014). This evidence shows that a large number of trucks without DPF on the road today may produce particles related to the SCR operation.

This study aims at characterising the particulate emissions from an SCR equipped HDD truck with no DPF, in conjunction to its NO_x emissions under real-world conditions and to derive real-world emission factors. In this context, three different emission factor calculation methods were compared, based on mean recorded levels or time-resolved data points. The suitability of each method in providing reasonable results for real-world emission factor production is discussed.

2. Methods

2.1. Testing and sampling

The experiments were performed on the road by measuring the concentration of CO_2, NO_x, and various particle characteristics, including particle size distribution, from the exhaust plume of an SCR-equipped Euro IV HDD truck. A semi-trailer was fitted to the vehicle and this operated on a regular service routing, between the cities of Oulu and Jyväskylä, Finland, on 22–23 September 2011. The total mass of the truck was 52,000 kg during the study. The route driven mostly consisted of relatively flat parts, especially near Oulu, and some moderately hilly parts. The driving speed of the vehicle was 80 km/h, and it only decreased due to insufficient power during uphill driving. This is a typical extra urban driving profile for such large trucks. The mean ambient temperature was 10.3 °C and the average relative humidity was 95.4%. The total duration of the measurement was approximately nine hours and was conducted in the evening, mainly during night hours.

Pollutant concentrations in the exhaust plume were studied by chasing the test vehicle with the "Sniffer" mobile laboratory (Pirjola et al., 2004). The exhaust was sampled at a distance of approximately 12 m downstream of the semi-trailer in the wake of the vehicle as this was driving, using a sampling probe with its inlet just above the front bumper of the mobile laboratory. Because the tailpipe of the vehicle was located just behind the cabin (0.5 m above the ground), the distance from the tailpipe outlet to the sampling location was close to 30 m. At this distance the total dilution ratio was approximately 2000:1 (Keskinen and Rönkkö, 2010) and the main aerosol ageing processes like dilution, cooling, primary nucleation and condensation of semi-volatile compounds were considered to be completed. The ageing time of exhaust aerosol between emission and sampling provides an aerosol condition which is similar to the particles that people at the roadside or in cars following a diesel vehicle are exposed to.

2.2. Instrumentation

An electrical low pressure impactor (ELPI, Dekati Inc.; Keskinen et al., 1992) with a filter stage (Marjamäki et al., 2002) and an additional impactor stage (Yli-Ojanperä et al., 2010) were used for real-time particle number and size distribution measurements. A condensation particle counter (CPC 3025, TSI Inc.) was used for real-time particle number concentration measurement. The ELPI measures aerodynamic particle size distribution and concentration from 7 nm to 10 μm while the CPC measures the total concentration of particles larger than 3 nm in diameter. Because of the maximum concentration limit (100,000 cm^{-3}) of the CPC 3025, a leaky filter diluter (LFD) with dilution ratio of 10:1 was installed upstream of the CPC. Two scanning mobility particle sizers (SMPSs) (Wang and Flagan, 1990) were used for particle size distribution measurements. One SMPS was equipped with a DMA 3085 (Chen et al., 1998) and a CPC 3025 (nano-SMPS, TSI Inc.). The other SMPS consisted of a DMA 3071 and a CPC 3775 (SMPS, TSI Inc.). The SMPS and nano-SMPS measured aerosol mobility diameters between 10–400 nm and 3–60 nm, respectively, both with a scan time of 120 s.

The instrument setup is shown in the Fig. S1 in the Supplementary material. Aerosol sample from inlet was fed directly to the instruments, but in certain occasions, it was first treated by a