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Particulate mass and number emission factors for road vehicles based on literature data and relevant gap filling methods

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HIGHLIGHTS

- Road vehicle particulate mass, total and solid number emission factors were developed.
- Emission factors were assigned to vehicle category, technology and fuel used.
- Size distributions to match particulate number and mass concentrations were synthesized.
- Consistent information that can be used for inventorying and policy assessment.

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ABSTRACT

This work presents a new set of exhaust particulate emission factors for light and heavy duty vehicles and different driving conditions (urban, rural and highway). The emission factors, building upon COPERT methodology, are expressed in terms of particulate mass (PM), particle number (PN) and as particle size distributions, addressing current and future vehicle technologies, as well as conventional and alternative fuels. All emission factors correspond to fine particles ($PM_{2.5}$), as the coarse fraction ($PM_{2.5\text{-}10}$) is negligible in primary vehicle emissions. PN emission factors refer to both total and solid particles to cover typical engine exhaust. The set of emission factors is a consistent set of information and can be useful to inventory compilers, air quality researchers and as input to impact assessment studies for policy options.

1. Introduction

Road transport is distinguished from most other sources of air pollutants in that its emissions are released near human receptors, significantly contributing to total population exposure to urban air pollution. Especially in the densely-built environment of city centres, vehicle exhaust pollutants are trapped within road canyons, forming local concentration hot-spots. For these reasons, traffic and its associated emissions have been directly linked to adverse health effects (HEI, 2010; Papapostolou et al., 2013).

In terms of particulate pollution, current air quality legislation in the European Union (EU) focuses on the regulation of fine particulate mass (PM) below 2.5 μm ($PM_{2.5}$) and total PM mass up to 10 μm (PM_{10}) (EC, 2015). However, ultrafine particles (UFPs < 100 nm) are suspected of being highly toxic because of their size and chemistry (HEI, 2013). The current pool of experimental and epidemiologic studies is inconclusive in terms of independent effects of UFPs on human health. This does not mean that such effects, as one part of the broader effects attributable to fine particles, can be entirely ruled out. UFPs seem to be at least as potent as fine particles for several health outcomes.

In vehicle exhaust, UFPs dominate the total number emissions and contribute less to the total mass (Eastwood, 2008). Most particle number in vehicle exhaust resides below 130 nm (Eastwood, 2008; Pant and Harrison, 2013) with little difference between diesel and gasoline vehicles. On the other hand, the peak in mass distribution is found for diesel particles in the range of 100–180 nm (Maricq et al., 2006). The exact characteristics of particle emissions from each vehicle depend on fuel and engine type, operation conditions, and exhaust aftertreatment technology.

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The importance of particulate emissions from gasoline vehicles has recently increased for two reasons. First, the use of diesel particle filters (DPFs) in the exhaust of all diesel vehicles has significantly reduced the relative and absolute contribution of diesel emissions. Second, port-fuel injection (PFI) is being superseded by direct injection (GDI) in modern gasoline cars, owing to its improved fuel efficiency. However, GDIs are known to be higher particulate emitters than PFIs (Karjalainen et al., 2014). For this reason, particle number (PN) emission standards are being enforced for GDI vehicles at the Euro 6 step.

Quantification of PM and PN emissions in vehicle exhaust for different technologies and fuels is therefore necessary to provide input to emissions inventories and to correctly assess the impact of gasoline and diesel combustion to air quality. Realistic emission factors are obtained either by dynamometer measurements based on real-world cycles simulating different driving conditions or, recently, by utilizing portable emission measurement systems (PEMS) to test individual vehicles operating in actual conditions on the road (Franco et al., 2013). Emission factors may also be derived by roadside measurements or combinations of methods (Keuken et al., 2016). Dynamometer-based emission factors are available in COPERT and the Emissions Inventory Guidebook for Euro 1 to 4 vehicles (PM emissions) and for Euro 1 to Euro 3 (PN emissions) (Ntziachristos and Samaras, 2014) and in HBEFA for Euro 1 to 6 vehicles (HBEFA, 2015). However, due to the lack of standardized testing conditions for pre-Euro 5/6 vehicles and the limited number of vehicles tested overall, the available PN emission factors in the different models are associated with high uncertainty.

The present paper aims to review and synthesize available literature with the aim to develop representative emission factors (EFs) for particulate matter and number exhaust emissions from different road vehicle technologies. Building upon COPERT4 methodology, it presents a comprehensive set of PM and PN EFs and particle size distributions (PSD) for passenger cars (PCs) and heavy duty vehicles (HDVs), ranging from pre Euro to Euro 6/VI emission standards and including both conventional and alternative fuels. Light commercial vehicles and buses/coaches are not specifically addressed, since no or very little information was found; however, as a first approximation, it can be considered that they can be approached to a certain extent by the PCs and the lower weight classes of HDVs.

2. Materials and methods

The development of EFs was based on the collection of information from different studies and subsequent statistical processing to derive representative average levels. Table 1 summarizes the individual vehicle categories for which EFs have been produced along with the method applied. Vehicles are grouped per type, fuel used, and capacity or weight class.

2.1. Particulate mass emission factors

PM exhaust levels for technologies earlier than Euro 5 (PCs) or Euro V (HDVs) were directly received from COPERT 4 (Ntziachristos and Samaras, 2014). COPERT 4 has been developed by compilation of emission data across Europe and has been validated in several studies by comparison with real-world measurements (e.g. Beddows and Harrison, 2008; Mellios et al., 2006; Kouridis et al., 2009). These values are designated with the symbol “C” in Table 1.

PM emission factors for Euro 5 and Euro 6 light duty vehicles, Euro V and VI HDVs and alternative fuels were derived by a combination of COPERT 4 and reported data from the different literature sources collected and analysed. In these cases, collation of studies with actual emission tests available in the public domain (see Tables A1 and A2 in Appendix A for details) was conducted. Only studies conducted with ultra-low sulphur fuels (diesel < 10 ppm and gasoline < 50 ppm for PCs and diesel < 15 ppm for HDVs) were considered. For biodiesel blends, nevertheless, the analysis included blends with neat diesel up to 50 ppm sulphur, since the number of studies conducted with ultra-low sulphur diesel (ULSD) as base fuel was limited. The measurements were grouped per the specific vehicle categories shown in Table 1 and the emission factors were the average of the collected measurements, distinguished per driving mode as explained below.

Despite our efforts, several gaps were still identified for many of the categories in Table 1. In these cases, specific gap filling procedures were devised.

For gasoline and diesel PCs compliant with Euro standards for which no measured information was found, emission factors were produced by application of emission limit (EL) equivalencies:

$$EF_{Euro\ i} = EF_{Euro\ i-1}\frac{EL_{\ Euro\ i}}{EL_{\ Euroi-1}} \tag{1}$$

This approach is designated as GF1 in Table 1. The same was also applied for Euro V HDVs, since Euro V was achieved without specific PM aftertreatment measures, but mostly engine improvements over Euro IV. Euro VI EFs were taken to be 90% lower than those of Euro V, considering both combustion improvements and the installation of DPFs in all vehicle types (Gense et al., 2006).

For EFs of alternative fuels, technological proximity and engineering assessment were utilized and, depending on the combustion principle, diesel or gasoline equivalencies have been used in these cases. For biodiesel and PCs, the EFs were derived assuming equivalency to fossil diesel emission levels per eq. (2),

$$EF_{B,Euro\ i} = EF_{B,Euro\ i-1}\frac{EF_{\ D,Euro\ i}}{EF_{\ D,Euroi-1}} \tag{2}$$

where $EF_{B,Euro\ i}$ and $EF_{D,Euro\ i}$ are the EFs of Euro i biodiesel and diesel vehicles correspondingly. Similarly, for ethanol, CNG and LPG passenger cars the EFs were derived by scaling the corresponding gasoline EFs, i.e.,

$$EF_{E,Euro\ i} = EF_{E,Euro\ i-1}\frac{EF_{\ GPFI,Euro\ i}}{EF_{\ GPFI,Euroi-1}} \tag{3}$$

This method is designated as GF2 in Table 1. In cases where no actual measurements were available (ethanol, CNG and LPG vehicles < 1.4 l), the EFs were taken equal to those of GPFI vehicles.

Finally, EFs for HDV with different biodiesel blends were developed using equivalent ratios for biodiesel use in PCs > 2 l, i.e.,

$$EF_{HDV,B,Euro\ i} = EF_{HDV,D,Euro\ i}\frac{EF_{\ PC,B,Euro\ i}}{EF_{\ PC,D,Euroi}} \tag{4}$$

where the ratio $EF_{\ PC,B,Euro\ i}/EF_{\ PC,D,Euroi}$ accounts for the effect of biodiesel blends on PM emissions compared to neat diesel. A similar approach was followed for the EFs of ethanol HDVs by applying the corresponding PC EF ratio which accounts for the effect of ethanol in comparison with neat gasoline. This is designated as GF3 in Table 1. For CNG HDVs from Euro I to Euro III, the EFs were based on the EMEP/EEA emission inventory guidebook data for buses, whereas EFs for Euro IV to Euro VI technologies were based on the results of buses reported by ICCT (2009) (designated as GF4 in Table 1). The equation used in this case was: