Particle Emission Factors of Different Vehicle Classes

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1. Introduction

Airborne particulate matter represents a complex mixture of organic and inorganic substances, varying in size, composition and origin. In the years 2005-2007, the 24-hour limit value for PM_{10} (50 $\mu g/m^3$) was exceeded more than 35 times a year in many European cities with 250,000 or more inhabitants.
In December 2007, the European Parliament voted for a limit on fine particles known as $PM_{2,5}$ (fine particulates below 2,5 µm): 25 micrograms a cubic meter will be a target in 2010 before becoming a binding limit in 2015. The EU seeks to limit $PM_{2,5}$ because it penetrates deeper into people's lungs, posing a greater threat of illnesses such as asthma and bronchitis and other serious health effects as well as of untimely deaths [1, 2].
Elevated concentrations of fine particles near busy roads indicate that road traffic is a major source of atmospheric particles [3]. Even if the greatest contribution is made by diesel-fuelled vehicles, all vehicle classes contribute with their own percentage to the increase in particle concentration in ambient air.
This paper aims to illustrate particulate emission factors, in terms of mass emitted (PM), total number concentration (PN) and size distribution, in the exhaust of different vehicle classes which most represent the circulating fleet in Italy. For this purpose an experimental campaign was carried out to quantify particulate emissions during driving cycles performed on a chassis-dynamometer with 10 vehicles.

2. Experimental set-up

2.1. Vehicle classes

The vehicle fleet is categorized in Table 1. It comprises 10 vehicles: 5 two-wheelers and 5 four-wheelers. The two-wheelers include 2-and 4-stroke mopeds with engine displacement of 50 cm^3. The four-wheelers include a light duty vehicle (van) equipped with a diesel particulate filter (DPF), and two gasoline and two diesel passenger cars without any after-treatment device for the particulate control. For each vehicle Table 1 reports the relative engine displacement and the European type-approval stage.
The experimental data are presented according to the category division (2-stroke mopeds, 4-stroke mopeds, diesel with DPF, gasoline and diesel without DPF) which is more representative of vehicle classes.

2.2. Driving cycle

Vehicles were tested during the driving cycle recommended by the European type approval procedure. Four-wheelers without discrimination between light-duty and passenger cars have to be tested on the New European Driving Cycle (NEDC) consisting of an urban (UDC) and extra-urban part (EUDC). The UDC includes 4 repetitions of the same module with a maximum speed of 50 km/h. During the EUDC, the maximum speed reached is 120 km/h. The NEDC has to be executed with cold start, that is the engine is kept off for at least 6 hours before the start of the cycle. The type approval driving cycle for mopeds is different. Known as ECE R47, it includes only an urban route consisting of 8 repetitions of the same module with a maximum speed of 45 km/h. The first four repetitions executed with cold start constitute the warm-up phase and last ones the sampling phase. Fig. 1 displays the speed trace of both NEDC and ECE47 cycles.

Class	***Category***	***Model***	***Engine displacement, cm³***	***European type approval stage***
Two wheelers	**2-Stroke mopeds**	Malaguti Ciak	50	Euro 1
		Kimco Dink	50	Euro 2
	4-Stroke mopeds	Piaggio Zip	50	Euro 1
		Honda Zoomer	50	Euro 2
		Piaggio Liberty	50	Euro 2
Light duty vehicle	**Diesel with DPF**	Mercedes Benz Sprinter	2150	Euro 4
Passenger cars	**Gasoline**	Opel Astra	1400	Euro 2
		Renault Megane	1600	Euro 3
	Diesel w/o DPF	Fiat Ulysse	2000	Euro 3
		Ford Mondeo	2000	Euro 3

Tab. 1 Vehicle fleet characteristics

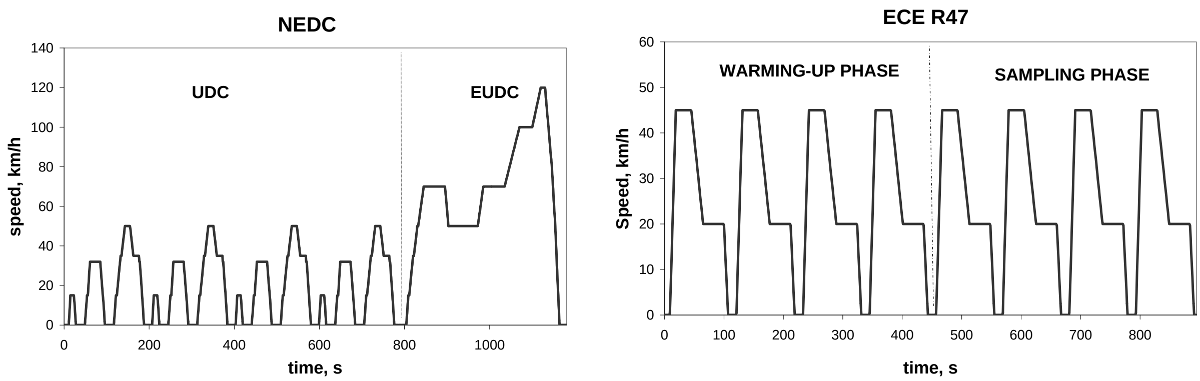

Fig.1 Speed trace of the NEDC and ECE R47 driving cycles

2.3. Particulate sampling

The type approval procedure forces particulate mass to be measured only at the exhaust of diesel vehicles. In this experimental work, the sampling procedure suggested by European legislation for diesel vehicles was used to quantify total particulate mass emissions for all vehicle categories. A sampling Teflon filter (PALL T60A20) was used to collect particulate during the whole duration of the driving cycle and mass emissions were evaluated by weighing the difference of the filter before and after the test. Sampling was carried out on diluted exhaust downstream of the dilution tunnel. Temperature over the sampling filter was always lower than 52 °C as recommended by legislation. Particle number concentration and size distribution were measured at the raw exhaust by using a low pressure impactor (Dekati-ELPI) coupled with a double-stage dilution system (Dekati-FPS). ELPI measures particles with an aerodynamic diameter between 7 nm to 10 μm. Dilution was controlled in temperature: the sampling probe was held at the constant temperature of 150 °C and the primary dilution air at 250°C. By using these temperatures and in the range of a dilution ratio between 15-50, primary dilution of exhaust was realized at almost 100 °C. Secondary dilution was cold. In order to evaluate emission factors of the particle number, exhaust flow was measured by using an exhaust flow meter (Sensors-EFM) based on the Pitot tube principle and also by comparing CO_2 concentrations measured in raw and diluted exhaust flows. In this way, instantaneous dilution ratios were estimated using a constant volume sampler device.

3. Results

The particle number concentration (PN), expressed as #/km, was calculated for each vehicle category. The results are plotted in Fig. 2.

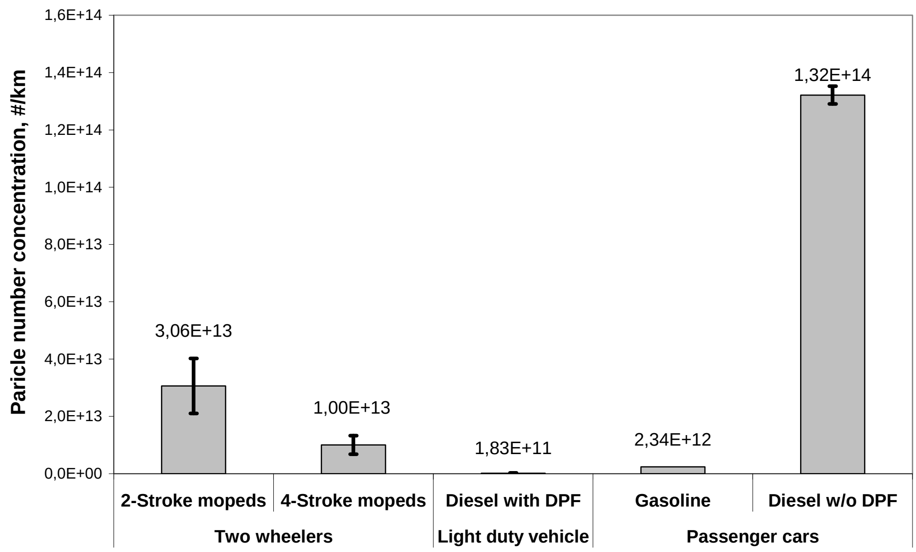

Fig.2 PN emissions

Diesel vehicles without DPF are the greatest particle emitters. Particle emissions follow the speed trace: a higher speed corresponds to a higher PN. The introduction of DPF at diesel exhaust has markedly reduced particle emissions which become almost two orders of magnitude lower. PN emissions of diesel with DPF include only cycles without regeneration which could markedly increase particle emissions [4]. The Diesel van equipped with DPF complies with the Euro6 PN standard limit proposal for diesel cars, $6x10^{11}$ #/km. This comparison needs clarification. The experimental set-up used in this work does not comply with the PMP legislative procedure proposal to evaluate particle number concentrations in vehicle exhausts.

Mopeds have particle emissions similar to those of diesel w/o DPF. A difference exists between 2- and 4-stroke. Particulate emissions of 2-stroke mopeds are almost three times higher than those of 4-stroke.

Gasoline vehicles have very low particle emissions which are comparable with diesel with DPF. Instantaneous emissions are less variable and not speed-dependent. Peaks of particle emissions occur during some rapid engine speed variations (gear changing, rapid acceleration).

As regards size distribution, an analysis was carried out to evaluate dimensions of particle emissions during constant speed phases of the driving cycle. Fig.3 shows particle size distribution measured in exhausts of 2- and 4-stroke mopeds at 20 and 45 km/h. It is evident that particles have a diameter lower than 1 μm with a peak occurring at almost 0,1 μm. For the examined fleet, 4-stroke mopeds have a greater contribution of larger particles (0,2-0,5 μm) than 2-stroke. This is explained by the presence in the 4-stroke category of a moped without catalyst. The absence of a catalyst enhances the agglomeration of particles in the exhaust pipe, thereby causing the formation of larger particles. Fig.4 shows particle size distribution at the exhaust of a diesel vehicle not equipped with DPF at idle, 32, 50 and 70 km/h. Besides the increase in particle number measured on 12 dimensional stages, particle distribution shifts to a higher aerodynamic diameter as speed increases from 32 to70 km/h.

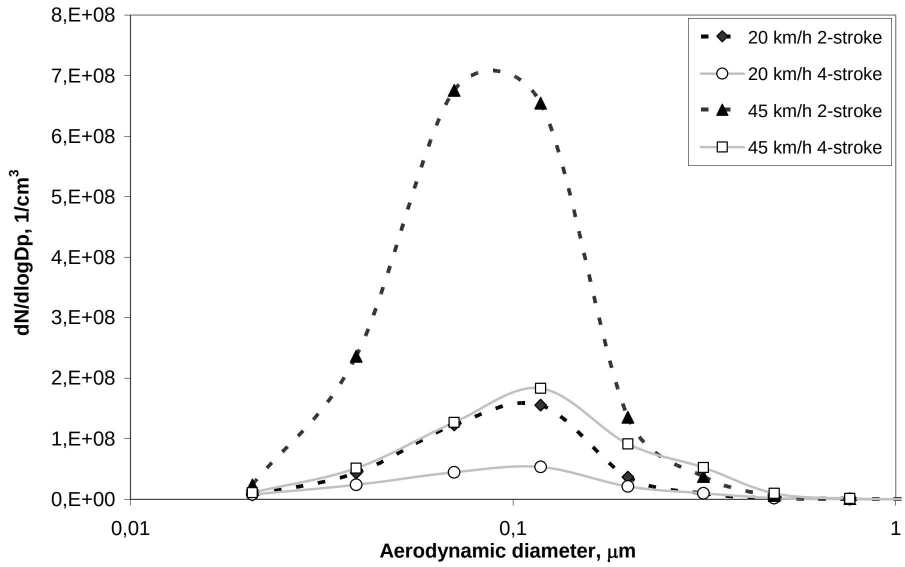

Fig.3 Particle size distribution in moped exhaust

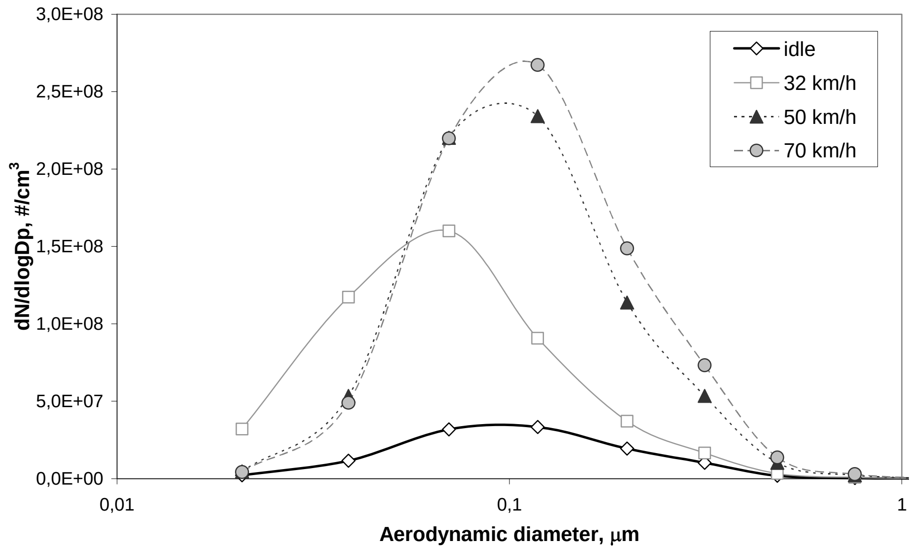

Fig.4 Particle size distribution in the exhaust of diesel van without DPF

This dimensional shift was not observed for the diesel vehicle with DPF. Fig. 5 plots the size distribution for this category at 30, 70 and 120 km/h. It appears evident that distribution always peaks at 70 nm.

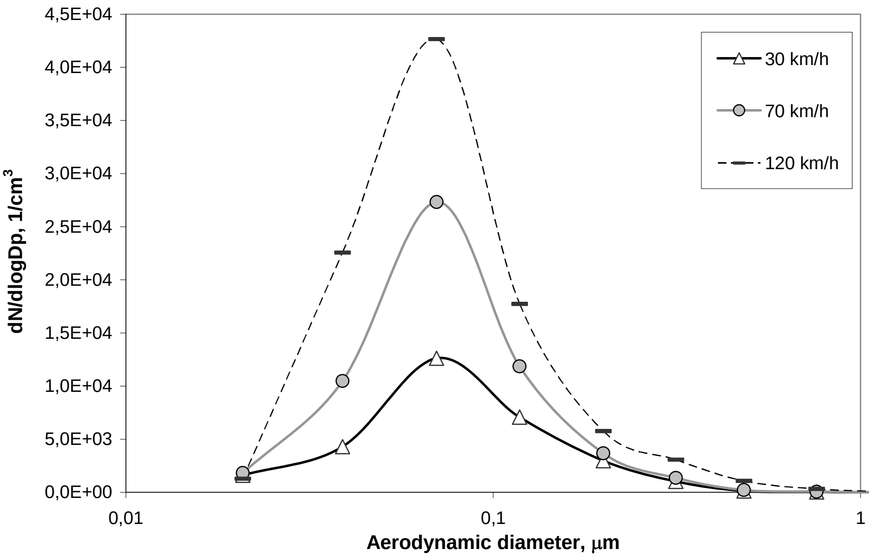

Fig.5 Particle size distribution in exhaust of diesel with DPF

DPF substantially decreases the mass of soot accumulation mode, whereas particle size distribution is dominated by nucleation mode [5, 6]. This phenomenon is strictly dependent on HC concentration in the absence of DPF and on sulfate formation in the presence of DPF [7]. In these experimental results, during tests carried out on the diesel vehicle with DPF sulfate formation was not enhanced due to the low temperature over the oxidation catalyst (lower than 300°C). This explains the similarity of distribution when changing speed. The diesel vehicle not equipped with DPF showed a decreasing trend in HC emissions corresponding to an increase in speed. In other words, when moving from 32 to 70 km/h, there is an almost 60% HC decrease with the consequent reduction of small particles formed by nucleation in the exhaust pipe.
A good correlation was found between particle number concentration and particulate matter. Fig.6 plots data points and relative linear interpolation corresponding to an R^2 of 0,87.

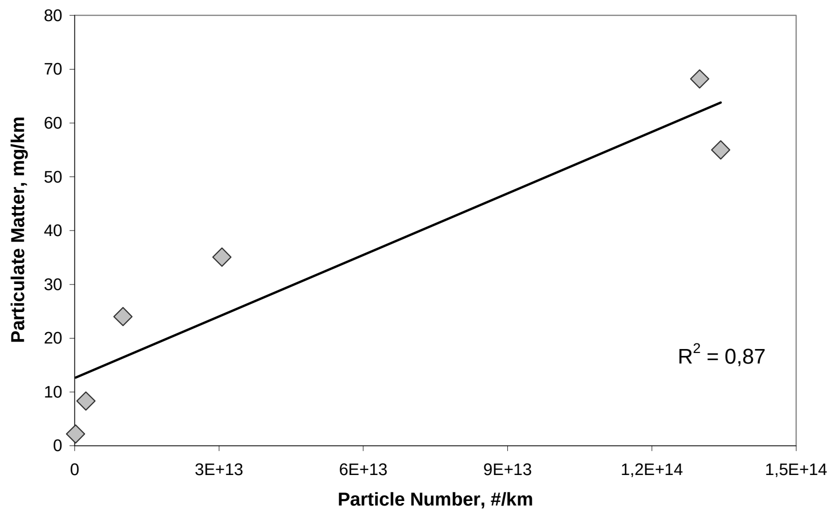

Fig.6 Particle Number vs Particulate Matter

This means that in the experimental conditions of these tests, the total particle number emissions were reduced almost to the same extent as the particulate masses. This aspect agrees with the almost total absence of a nucleation mode which could have determined a lower reduction of particle numbers [8].

4. Conclusions

An analysis of the particulate emissions in terms of number, dimensional distribution and mass was carried out on the exhaust of different vehicle classes: mopeds, gasoline and diesel (without DPF) passenger cars and diesel light-duty with DPF.
The main conclusions of this study are:

- Diesel vehicles without DPF and mopeds have the highest PN and PM emissions [9]. Among mopeds, 2-stroke are more emissive than 4-stroke.
- The introduction of DPF at diesel exhaust reduces particle emissions by almost two orders of magnitude.
- Under the specific experimental conditions used in these tests the nucleation mode was not visible. We observed only an increase in the aerodynamic diameter when increasing speed was registered in the exhaust of diesel without DPF due to a corresponding decrease in HC.
- There is a good linear correlation between PN and PM (R^2=0,87).

5. References

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