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Comparison of PM production in gasoline and diesel engine exhaust gases

M. Kotek*, P. Jindra, P. Prikner and J. Mařík

Czech University of Life Science Prague, Faculty of Engineering, Department of Vehicles and Ground Transport, Kamýcká 129, CZ165 21 Prague, Czech Republic
*Correspondence: kotekm@oikt.czu.cz

Abstract. The article is focused on different kind of combustion engines and their particulate matter production. The first part of experiments dealt with particulate matter production under defined driving cycle and operating regimes. The second part of experiments was carried out to measure the maximal PM production under engine's full load regime. The experimental vehicle engines were manufactured by Skoda Auto a.s., equipped with modern fuel injection systems. Two representatives of diesel engines were chosen: the engine EURO-4 1.4 TDI with PD (Unit injector) injection system and the EURO-6 1.6 TDI with common rail injection system and DPF. As two representatives of gasoline EURO-4 engines were chosen: 1.2 MPI with non-direct fuel injection system and 2.0 FSI with direct stratified fuel injection system. The analysis of the particulate matters was carried out on a TSI Engine Exhaust Particle Sizer 3090 that is able to classify particles from 5.6 nm to 560 nm. In the case of diesel engines the results proved expectable decrease in PM production due to usage of diesel particulate filter (DPF). The older engine without DPF produced more than hundred times higher PM production under all operating regimes of driving cycle. The result of gasoline engines confirmed increased PM production of direct injection systems especially under higher engine load. FSI engine in driving cycle reached up twenty times higher PM production than MPI engine.

Key words: particulate matter, MPI, FSI, DPF, PFI, common rail, carburettor, size distribution, driving cycle.

INTRODUCTION

The diesel engines are often used in trucks, trains and other heavy-duty applications, as a powertrain. The number of diesel vehicles slowly equals the number of vehicles with gasoline engines. In the European Union share of diesel engines was about 41% in 2014 (ACEA). This fact leads to very strict regulations limiting the emission production which manufacturers must respect.

First emission limit Euro-1 was introduced in 1992. Euro-2 in 1996, Euro-3 in 2000, Euro-4 in 2005, Euro-5 in 2009 and last Euro-6 was introduced in 2014. To meet the strict Euro-6 limits the new vehicles have to be equipped with the diesel particulate filter (DPF) for PM reducing and with the SCR (selective catalytic reduction) catalyst to meet the NO_X limits (López et al., 2009).

The most frequently discussed problem of diesel engine emissions are particulate matter (PM) and nitrogen oxides (NOx). The danger of PM lies in the ability to absorb polycyclic aromatic hydrocarbons (Vojtíšek-Lom et al., 2015). Impact of increasing PM production on human health is often associated with lung cancer and asthma (McEntee et al., 2008).

Size of PM influences the impact on human health. Particles less than tens of nanometres can penetrate through cell membranes into the blood and have a wide and detrimental effect on human health (Künzli et al., 2000). PM may affect reproduction, cardiovascular system or may provoke cancerous growth (Lewtas, 2007).

The number of gasoline direct injection (GDI) engines grows in recent years because of its advantages in terms of fuel economy. The introduction of direct fuel injection to gasoline engines has led to an increase in fuel economy and engine performance in relation to traditional port injection (Mathis et al., 2005). Explanation is that the direct injection allows better control the quantity of fuel injected and because vaporized liquid droplets cause a cooling of surrounding air and it allows to increase air volume in a cylinder. On the other side there is not enough time in GDI engines for complete fuel evaporation which leads to the formation of areas with a locally rich mixture. Therefore more particulate matter is produced from GDI engines compared with PFI engines (Liu, 2013; Short, 2015).

Comparing the production of vehicles according to the PM with depending on the emission standard was solved by Tzamkiozis, 2010. Emissions from actual operations and their dependence to speed or age of vehicle describes Chana, 2004. One of possible way is to reduce the production of PM by the use of alternative fuels or biofuels. A common alternative fuel is LPG. Emissions during the use of LPG in real operation describe Laua, 2011. Positive impact of biofuels in terms of engine emissions was confirmed by many studies (Mařík et al., 2014; Pexa et al., 2014, Kotek et al., 2015; Jindra et al., 2016). But on the other hand emission production is substantially influenced by the driver's behaviour and immediate traffic conditions (Holmén & Niemeier, 1998). Vehicle manufacturers try to solve the problems linked with emissions in several ways.

One the most discussed issue, especially within recent years, is well known scandal so-called 'Dieselgate' that is associated with the excessive production of emissions by several types of VW's diesel engines. The general public is influenced by the media campaign against the use of diesel engines, mainly in case of older engines due to the excessive production of NO_X emissions and particulate matter. Many automobile manufacturers announced a planned limitation of diesel engine production till the year 2020. On the contrary, the use of gasoline direct injection engines is more and more supported but in fact they can produce a significantly higher amount of PM than the diesel engines which are already mandatorily equipped with diesel particulate filters.

This article presents a comparison of the PM production depending on the engine type (spark ignition, compression ignition) and fuel injection system operating at various operating modes.

Five different vehicles from Skoda Auto, a.s. were used for this experiment. The vehicles were manufactured in the years 2004–2016. For better illustrations of development in systems for emission reducing the experiment was extended by the historic Skoda Octavia manufactured in 1960.

MATERIALS AND METHODS

The five different vehicles Skoda (technical information see Table 1) were used in these experiments. Three vehicles were equipped with spark ignition (SI) engine and two with compression ignition (CI) engine.

Table 1. Technical information of tested cars

					
Vehicle	Octavia 2.0 FSI combi	Fabia 1.2 HTP	Rapid 1.6 TDI Spaceback	Roomster 1.4 TDI	Octavia Super 1960
COMBUSTION ENGINE					
Design	SI, atmospheric	SI, atmospheric	CI, turbo charged	CI, turbo charged	SI, atmospheric
Fuel system	direct injection	multi-point injection	common rail	unit injector system	carburettor
Number of cylinders and valves	4, in row, 16 valves	3 in row, 6 valves	4, in row, 16 valves	3 in row, 6 valves	4, in row, 8 valves
Fuel	gasoline	gasoline	diesel	diesel	gasoline
Volume of cylinders	1,984 ccm	1,198 ccm	1,598 ccm	1,422 ccm	1,433 ccm
Power	110 kW at 6,000 rpm	40 kW at 4,750 rpm	85 kW at 4,400 rpm	59 kW at 4,000 rpm	37.5 kW at 4,600 rpm
Torque	200 Nm at 3,500 rpm	106 Nm at 3,000 rpm	250 Nm at 1,500 rpm	195 Nm at 2,200 rpm	88 Nm at 3,000 rpm
EU limit	EU4	EU4	EU6	EU4	EU0
PM limit	-	-	0.005 g·km^{-1}	0.025 g·km^{-1}	-
Manufacture year	2004	2003	2016	2006	1960 (engine 1990)
Mileage	105,000 km	136,000 km	12,500 km	102,000 km	65,000 km
CAR BODY					
Service weight	1,515 kg	1,055 kg	1,260 kg	1,240 kg	920 kg
DRIVE PERFORMANCE					
Max. speed	212 km h^{-1}	150 km h^{-1}	190 km h^{-1}	165 km h^{-1}	115 km h^{-1}
Acceleration 0–100 km h^{-1}	9.4 s	18.5 s	10.3 s	14.7 s	-
Fuel consumption	8.87/5.18/6.5 (L 100 km^{-1})	7.8/4.8/5.9 (L 100 km^{-1})	5.0/3.4/4.1 (L 100 km^{-1})	5.1/3.76/4.26 (L 100 km^{-1})	8 (L 100 km^{-1})

The experiment was conducted on the chassis dynamometer at the Department of Vehicles and Ground transport, CULS in Prague. This device simulated the real driving resistances according to each vehicle properties. Test procedure was split into two stages.

In the first stage the vehicles were driven according to designed driving cycle (specification see Fig. 1) to attain repeatability and comparability of conducted measurements under conditions that were as close as possible to real driving conditions. This driving cycle was based on the NEDC (New European Driving Cycle), but for the purpose of this experiment was substantially shortened and maximal speed was limited up to 80 km h^{-1}.

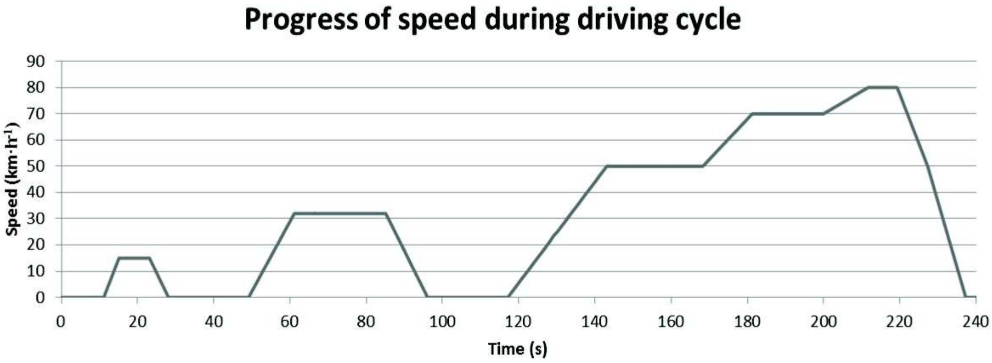

Figure 1. Progress of speed during driving cycle.

The second stage of test procedure was focused on to measure the maximal PM production at full load of engine. The vehicle was driven on chassis dynamometer again; at 3rd gear grade from idle to maximum engine speed with full acceleration. This regime was repeated 3 times.

Classification of PM was analysed by the engine exhaust particle sizer TSI model EEPS 3090 whose detailed specification is shown in Table 2. The analyser enables detection of particle size and also monitors their number. The obtained data are presented as a size range of produced particles. The measured sample was taken from the exhaust gas, and then is diluted by the device. Within the experiments were evaluated only relative changes in the production of solid particles in the diluted exhaust gas.

Table 2. Specification of PM analyser TSI EEPS 3090

Particle size range	5.6–560 nm
Particle size resolution	16 channels per decade (32 total)
Electrometer channels	20
Time resolution	10 size distribution per second
Sample flow	10 L min^{-1}
Dilution accessories	Rotation Disk thermodilution

RESULTS AND DISCUSSION

The result of instantaneous values of PM total concentration during driving cycle for each vehicle is shown in Fig. 2.

The highest PM values were reached by the vehicle Skoda Roomster. This vehicle produced high amount of PM already even at idling speed (compared to other vehicles) and the next increase of PM production is evident under engine load. The second vehicle with CI engine Skoda Rapid reached expectable minimal PM concentration during the whole cycle due to diesel particulate filter (DPF). There is no noticeable influence of engine operating state on PM production which indicates a very high DPF efficiency. This observation is consistent with Mathis et al. (2005) and Mohr et al. (2006).

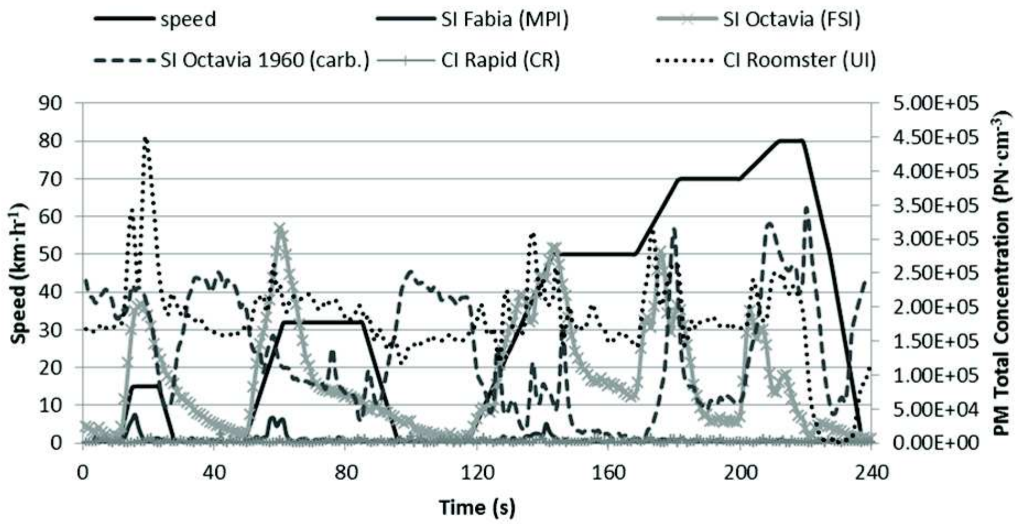

Figure 2. PM total concentration during driving cycle.

In case of vehicles with SI engines the situation is a little complicated. The lowest PM concentration was reached by Skoda Fabia with relatively obsolete non-direct multi-point injection system. On the other hand the vehicle Skoda Octavia FSI with modern direct system of stratified injection produced the highest values of PM. It is probably caused due to combustion strategy. FSI engine management switched from the stoichiometric mode to the lean stratified combustion which caused significantly higher particle emissions especially at higher engine load. A similar conclusion was reached by Mohr et al. (2006) and Chen et al. (2017). The last vehicle Skoda Octavia 1960 was in experiment as interesting attraction and produced expectable very high amount of PM. There was not surprisingly so big difference in the PM production compared to Octavia FSI that is about 40 years younger. It can be caused probably by a big influence of very rich mixture prepared by old carburettor system because of illogical decrease in PM production at higher engine load and increase at idle.

Better overview of reached results is provided in Fig. 3. There are shown average values of PM production during whole driving cycle and separately at idling speed. These two presented regimes demonstrate the influence of engine load. There are not evident fundamental differences between idle and ordinary operating state for Skoda Roomster and Octavia 1960. These vehicles produce almost constantly large amount of PM regardless to engine operating state while Skoda Rapid and Skoda Fabia produced the minimal amount of PM during the whole driving cycle. These results are consistent with Mathis et al. (2005), Mohr et al. (2006) and Chen et al. (2017).

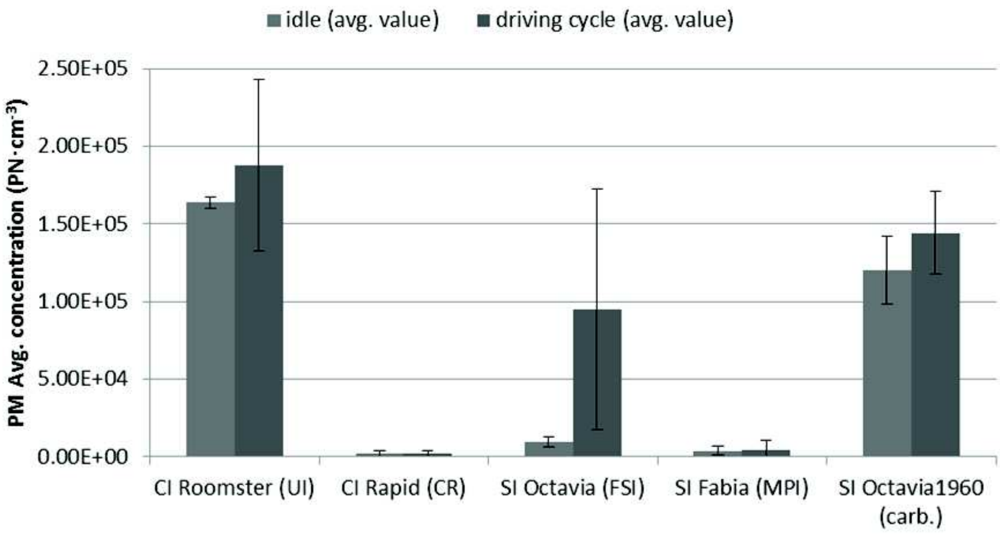

Figure 3. PM average PM concentration during driving cycle and at idle speed.

The results of second stage of experiment are summarised in Fig. 4. There is evident surprisingly the highest PM production of Skoda Fabia MPI. Results of other vehicles correspond approximately to previous Fig. 3. It is important to remark that engine works relatively exceptionally at operating regime of full load during normal drives.

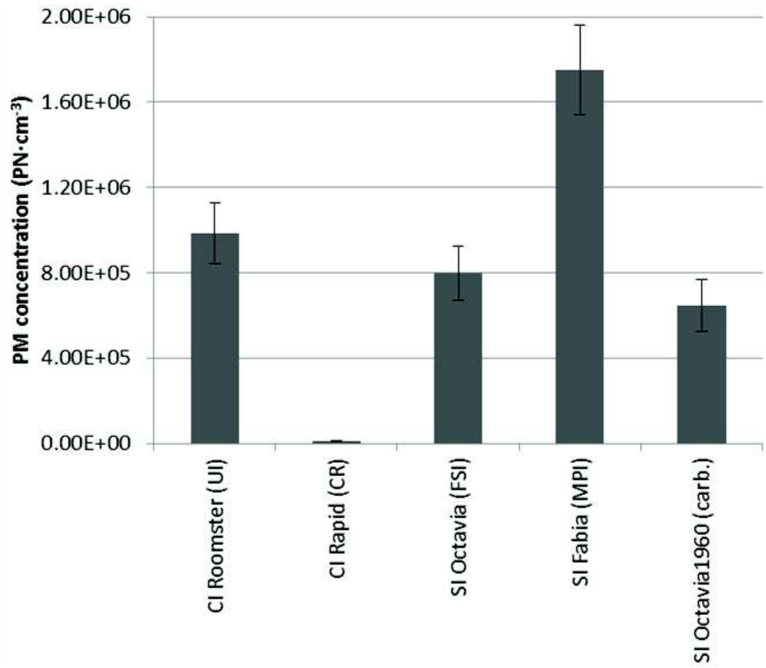

Figure 4. Maximal PM concentration at full load.

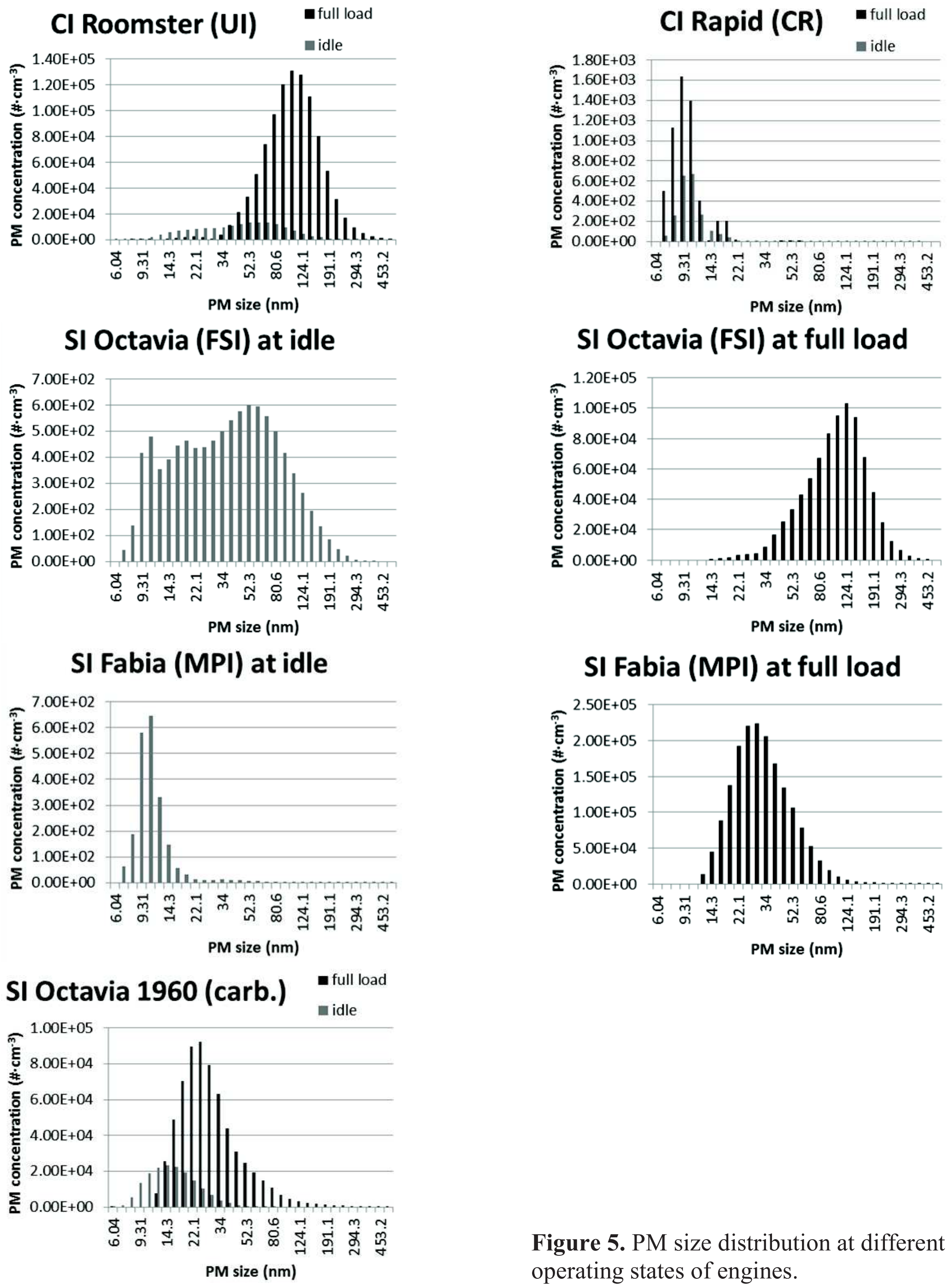

Figure 5. PM size distribution at different operating states of engines.

The Fig. 5 shows PM size distribution at idle speed and at full engine load (respectively at maximal PM production). The vehicle Skoda Roomster produces relatively large PM at both operating regimes. The similar situation is at full load of Skoda Octavia FSI while at idling speed was produced wide PM spectrum but with very small total concentration. Much better situation is in the case of Skoda Rapid with DPF. There are evident filter abilities of DPF when the PM spectrum decreases up to minimal size and PM total concentration is very low. Skoda Fabia MPI produced very small size and amount of PM at idling speed while at full load the PM spectrum is shifted to middle and the total concentration rapidly grows. Similar PM size distribution can be found in Gupta et al. (2010) and Graves et al. (2017). In case of historic Skoda Octavia 1960 the PM spectrum at idle is little bit similar to Skoda Roomster when the spectrum is shifted to small particles. At full load the PM spectrum is very similar to all other SI engines, the spectrum is again shifted to small particles but the total concentration is the smallest of tested SI engines.

CONCLUSIONS

This paper was focused on measurement of PM (particle number and particle size distribution) emitted from the exhaust of different types of SI and CI engines.

The results of PM production of CI engines confirm that newer vehicles with modern system of fuel injection (common rail) and better systems for emissions reduction (especially DPF) produce absolutely minimal PM. Of course there is a question what happens in case of DPF regeneration process when can be expectable big increase in PM production as was published for example in Ko et al. (2016).

In case of SI engines there is different situation. The older system of non-direct multi-point injection reached minimal PM production (except of full engine load) while the newest direct fuel stratified injection system showed perceptible increase at every engine load. The twenty times higher PM production was reached in driving cycle in compare with MPI engine. It can be expected that in the future DPF could be mandatory for new gasoline engines with FSI technology.

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