AN INVESTIGATION OF INFLUENCE OF DIESEL FUEL SULPHUR CONTENT ON PARTICULATES EMISSIONS FROM DIRECT INJECTION COMMON RAIL DIESEL VEHICLE

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Abstract

The motor vehicle is one of the main sources of pollutant emissions, especially in urban areas. Environmentally friendly fuels are regarded as very effective means to decrease emissions. With regard to diesel engines, the reduction in nitrogen oxides and particulates are major problem areas. Although the fuel influence on no_x *is comparatively low, the composition and parameters of diesel fuel have a big influence on particulate emissions and composition. Sulphur content is one of fuel proprieties, which has the most considerable influence on particulates.*

This paper describes results of the research on particulate emissions from direct-injection common- rail (DI CR) diesel vehicle fuelled with research fuels of differing sulphur content. The sulphur content of the research fuels varied from 2000 ppm through 350 ppm (EURO III) and 50 ppm (EURO IV limit, which will be in force in the European Community from 1 January 2005) up to less than 5 ppm. The experiment was undertaken on a passenger car with an high-speed, four-cylinder turbocharged, latest technology diesel engine with swept volume of about 2 dm^3*. The experiments confirmed the distinct influence of sulphur content in diesel fuel on particulate emissions. Therefore, the sulphur content in diesel fuels should be reduced further.*

1. Introduction

Internal combustion engines, operating primarily on petroleum-based fuels, dominate land transportation propulsion. They also play the major role in marine and light aircraft propulsion. Due to the lower fuel costs associated with diesel engines, these engines are used extensively in transportation systems. It is well known that the direct-injection diesel engine is the most effective among internal combustion engines because of its excellent thermal efficiency and durability. Direct injection diesel engines minimise the green house effect because its low fuel consumption leads to low CO_2 emission. On the other hand, a further significant reduction of particulate matter (PM) to meet stringent environment regulations remains to be addressed.

The growing interest and awareness of environmental health and safety issues among the public and authorities has focused attention on exhaust emissions [12]. The amount of particulates in the engine exhaust and the composition of exhaust particulates have become the most interesting topics among the pollutant exhaust emissions. The International Agency for Research on Cancer (IARC) has defined diesel exhaust as a probable carcinogen to humans [9].

That's why the reduction of particulate emissions is one of the most serious problems for diesel engines.

Particulate matter emitted in diesel exhaust is a complex mixture of carbon particles of soot, unburned fuel and lubricants and perhaps fuel pyrolysis products, which make up the soluble organic fraction (SOF) and sulphates plus water. The particulate emissions produced by a diesel engine are a function of a number of parameters, for example: engine type, engine operating conditions, and catalyst type and fuel composition.

To meet new, unusually severe norms of PM emission (for instance: Euro III, IV and V, Tier 2, ULEV, LEV II) single solution will no longer be sufficient. Complex activities including: optimisation of the process of fuel combustion in the engine by improvement of its construction, introducing systems (e.g. EGR) restraining the formation of pollutants, use of effective catalytic systems for emission control and finally appropriate blending of fuels are necessary.

Fuel composition as well as physical and chemical parameters have, apart from the type of engine and its condition decisive influence on the quantity and constitution of emissions [11, 17]. Each parameter of engine fuel affects emissions, in three key areas:

- by influence on injection parameters,
- by connection with creation of pollutant matter in engine,
- by influence on efficiency of emission control systems.

Sulphur content is one of fuel proprieties, which has the most influence on particulates [16]. In a combustion process most of sulphur (about 95-98%) contained in diesel oil is being oxidized to SO_2, which together with exhaust gas from the exhaust system is then mostly vented into the atmosphere where it can be subject to other reactions contributing to the creation of the London type smog and acid rain. However, some of SO_2 in a presence of oxygen can be unfavourably oxidized to SO_3. The high temperature of exhaust gas means that SO_3 stays in a vapour state and easily combines with water formed in the combustion process. In an exothermic reaction the aerosol of the sulphuric acid is formed which together with the chemically bound water becomes a component of the PM emission [8, 15].

Moreover, some sulphur oxides formed during the combustion process combine with hydrocarbons or metals forming sulphates – another component of particulate matter. Metals originate from the products of the engine reciprocating and rubbing abrasion as well as from lubricating oil, fuel (catalyst residue) or erosion of the catalytic emission control systems [14]. If there is no catalytic reactor in the engine exhaust system, the efficiency of the process of transformation of sulphur contained in fuel into sulphates is about 1%. This process can be much more intensive in the case of engines equipped with catalysts, especially in the case of oxidizing units. This effect is promoted by: the platinum present in the composition of the active layer and the high temperature of exhaust gas [18, 19]. Thus with the increased sulphur content in diesel fuel the total PM emissions increases and also changes its composition.

Described in literature research programs concerning the influence of fuels on emission levels, confirm the negative sulphur effect on particulate emissions [1, 3, 4, 5, 6, 7, 10, 11, 13]. It is also characteristic, that the sulphur effect on particulate emissions depends on other proprieties of diesel fuel and on the engine type. So far there have been no such research taking into account Polish conditions, e.g. specification of Polish vehicles fleet as well as Polish fuels. Therefore it was difficult to predict ecological benefits obtained due to lower sulphur contents in Polish diesel fuels. The goal of the research project described in this paper was to fill this gap.

The very permissive regulations of the PN-EN 590:1999 standard (Table 1) which is currently valid in Poland in relation to diesel fuel were the second reason which made the authors undertake the study concerning the influence of the sulphur content on particulate emissions. In fact, the requirements of the PN-EN 590:1999 standard practically do not consider the aspect of the influence of fuel composition on the formation of exhaust emissions. In such situation, in Poland there is a high potential for reducing the exhaust emissions through the improvement of fuels and above all by lowering the sulphur content. It has to be remembered, that there is still a significant number of old vehicles in operation in Poland, for which using the eco-fuels can be the only reasonable way to limit noxious emissions. Facing the decision of joining the European Community Poland will have to adjust the quality of its fuels to that of Europe.

Table 1

Comparison of requirements for diesel fuels

	PN-EN 590: 1999[1)]	EURO III (2000)[2)]	EURO IV (2005)[2)]	WFC[3)] Category 4
Cetane number	min 49	min 51	?	min 55
Sulphur, ppm	max 2000	max 350	max 50	max 5–10[4)]
Polyaromatics, % m/m	-	max 11	?	max 1.0
Density @15°C, kg/m^3	820–860	max 845	?	820–840
Distillation	E370 = min 95 % (v/v)	T95 = max 360°C	?	T95 = max 340°C

[1)] Polish Standard, [2)] European Directive 98/70 [3)] Worldwide Fuel Charter, [4)] accurate maximum will be defined

A number of previous studies have investigated the effect of diesel fuel properties on steady-state and transient emissions, but the sulphur content was not usually taken into account as experimental variable and the sulphur effect was distorted by other fuel properties. In the present work sulphur content is the only fuel design variable and is varied from 2000 ppm down to sulphur free (less then 5 ppm S).

2. Research project

The present research work was conducted in collaboration between BOSMAL Automotive R&D Centre and Institute of Internal Combustion Engines at Poznan University of Technology. The tests were conducted on a passenger car equipped with 1.9 litre direct injection (common-rail) turbocharged engine, representing the latest technology in production at the start of the research programme. Major data on the vehicle are shown in Table 2.

Table 2

Specifications of the test vehicle

Vehicle Type	Passenger Car
Dry Weight	1300 kg
Engine Type	Diesel, 4-cylinder in-line
Displacement	1.9 litre
Injection / Combustion Type	Direct injection common-rail, turbocharged (intercooled)
Exhaust Gas Recirculation	Electronically controlled (closed-loop)
Emission control technology	Oxidation catalyst
Calibrated to	EURO III

The new vehicle homologation procedure introduced in the Directive 98/69/EC, called as New European Driving Cycle NEDC (Fig. 1) was selected as a representative test for this study.

The test was Urban Driving Cycle (UDC) (cold start), followed by the high-speed Extra Urban Driving Cycle (EUDC) (hot start). Tests were undertaken in order to determine the influence of both parts of NEDC cycle on total particulate emissions. Results for all measured pollutants are presented in grams per kilometre travelled during the cycle or individual phase of the cycle.

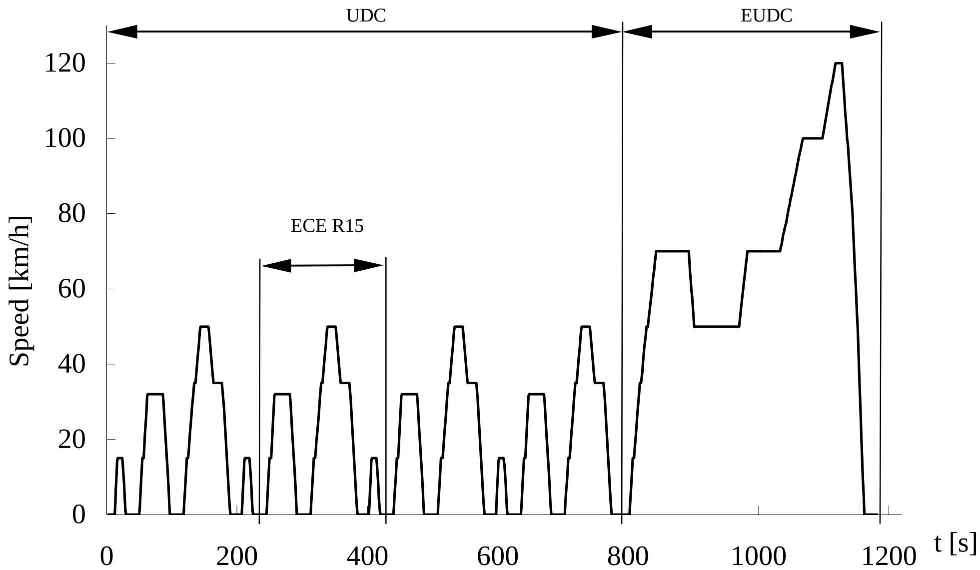

Fig. 1. *New European Driving Cycle*

The tests were carried out at BOSMAL Automotive R&D Centre's Emission Testing Laboratory using an emission chassis dynamometer Schenck 500/GS60 (Fig. 2). The CVS AVL CEC system with full-flow dilution tunnel AVL CET-LD/20 type (Fig. 3) and particulate sampling system AVL CEP-LD/100 PTS 60 l/min (Fig. 4) and Sartorius microbalance have been used to measure exhaust mass particulate emissions.

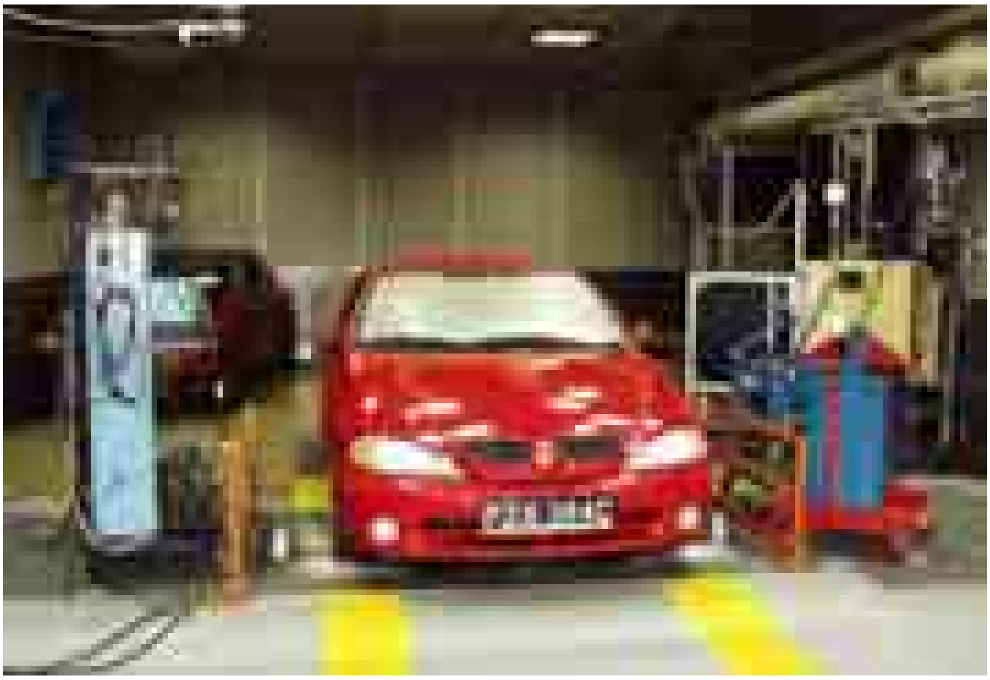

Fig. 2. *Emission Testing Laboratory of the BOSMAL Automotive R&D Centre*

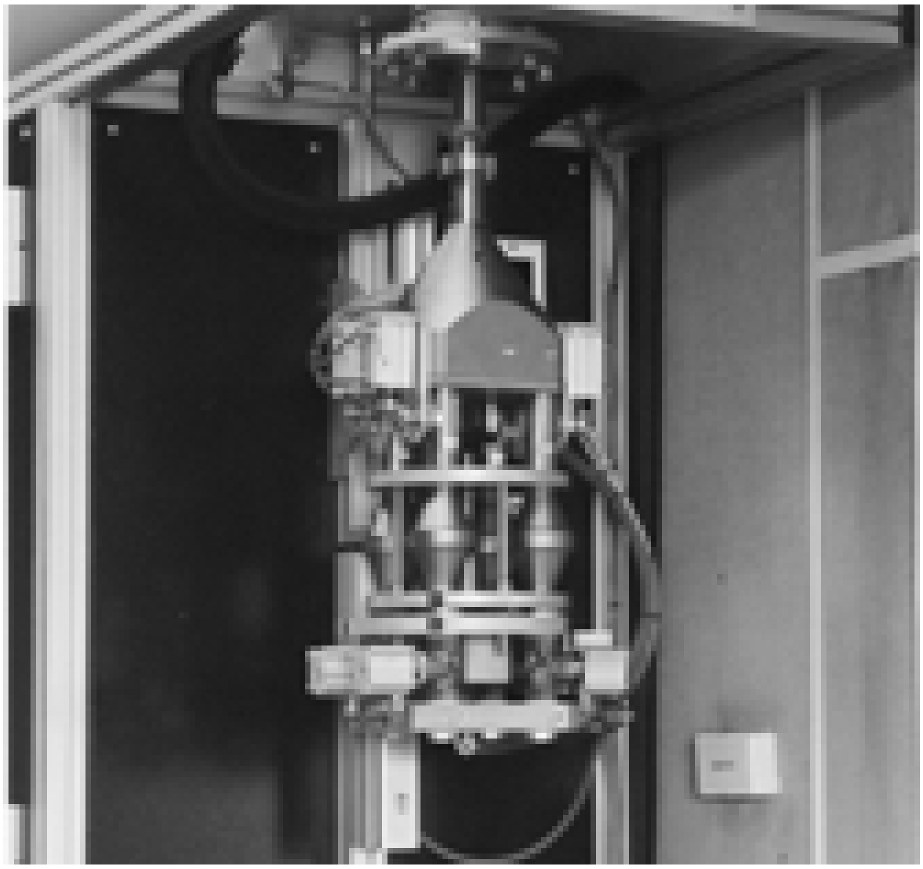

Fig. 3. *A view of particulate sampling unit*

Fig. 4. *Emission Testing Laboratory of the BOSMAL Automotive R&D Centre- dilution tunnel*

To evaluate the influence of sulphur contained in diesel fuel on the particulate emission four different test fuels with the sulphur content varying from less than 5 ppm through 50 ppm (EURO IV) and 350 ppm (EURO III) up to 2000 ppm were prepared. The test fuels were blended on the basis of sulphur free (<5 ppm S) diesel fuel from Polish refinery. The expected level of sulphur content was being obtained after addition of the right amount of thiophene (C_4H_4S). The properties of test fuels are shown in Table 3.

Table 3

Test Fuel Properties

		TF-1	TF-2	TF-3	TF-4
Sulphur, ppm		**2000**	**350**	**50**	**<5**
Cetane Number		52	52	52	52
Density @15°C, g/ml		0.815	0.815	0.815	0.815
Aromatics, % (v/v)		5.1	5.1	5.1	5.1
Distillation	IBP, °C	172.0	172.0	172.0	172.0
	T50, °C	255.9	255.9	255.9	255.9
	T90, °C	303.6	303.6	303.6	303.6
	FBP, °C	340.5	340.5	340.5	340.5

3. Test results and discussion

The results of measurements of the PM emissions obtained in the NEDC tests at the chassis dynamometer when supplying the test vehicle with fuel with different sulphur content are presented in Figures 5, 6, 7 and 8.

The Figure 5 presents the PM emission in exhaust gas as a function of the fuel sulphur content of a passenger car with the DI CR engine equipped with the oxidation catalyst during the NEDC test. The same results presented in a percentage form are shown in Figure 6. As expected the highest PM emission was obtained at the highest sulphur content in diesel fuel. For other fuels the PM emissions were of a similar value and about 20% lower than for the case with 2000 ppm sulphur content. For fuels with the 350 and 50 ppm sulphur content the same PM emission levels were recorded which were higher by only less than 4 % than for diesel oil of a sulphur-free type.

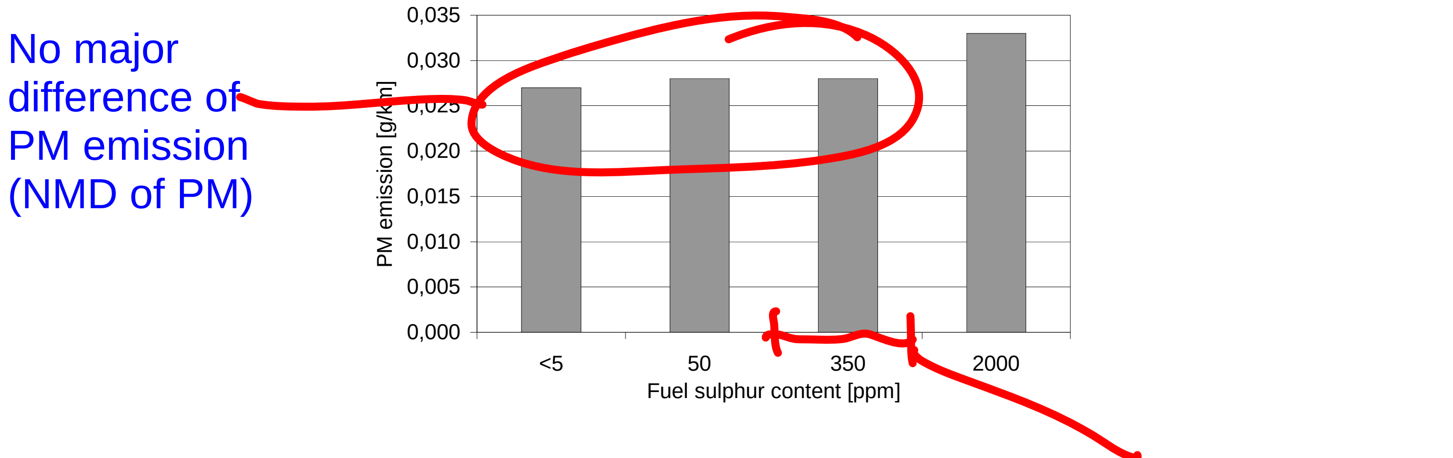

Fig. 5. *PM emissions during NEDC (UDC+EUDC) as a function of diesel fuel sulphur content*

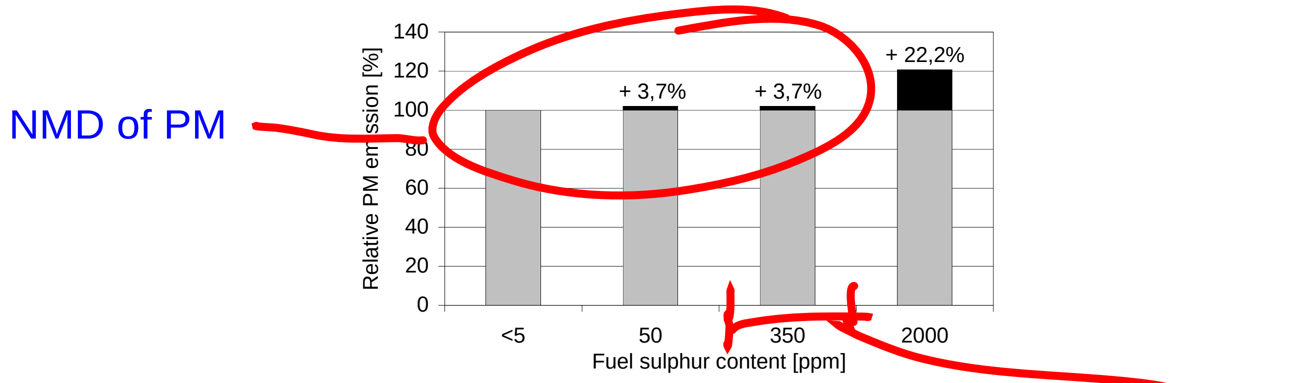

Fig. 6. *The percentage increase of PM emission during NEDC as a result of fuel sulphur content increase*

When analysing the PM emissions (Fig. 7) during the UDC test, which makes up the first part of the NEDC test, it should be stated that the PM emission differences obtained here for the fuels with the extreme values of sulphur content are lower than for the complete NEDC test. It is probably due to a low temperature of the catalyst and exhaust gas in this test, resulting from the cold start and small engine loads. It follows that the formation of the sulphates occur with reduced intensity and effects the total PM emission level to a smaller extent.

In the second part of the NEDC test, namely during the EUDC test (Fig. 8), the linear relation between the PM emission and the sulphur content in fuel was obtained. It should be concluded that the exhaust gas and catalyst temperatures were higher (hot start, higher load) than during the UDC test and as a result the increased formation of the sulphates were decisive.

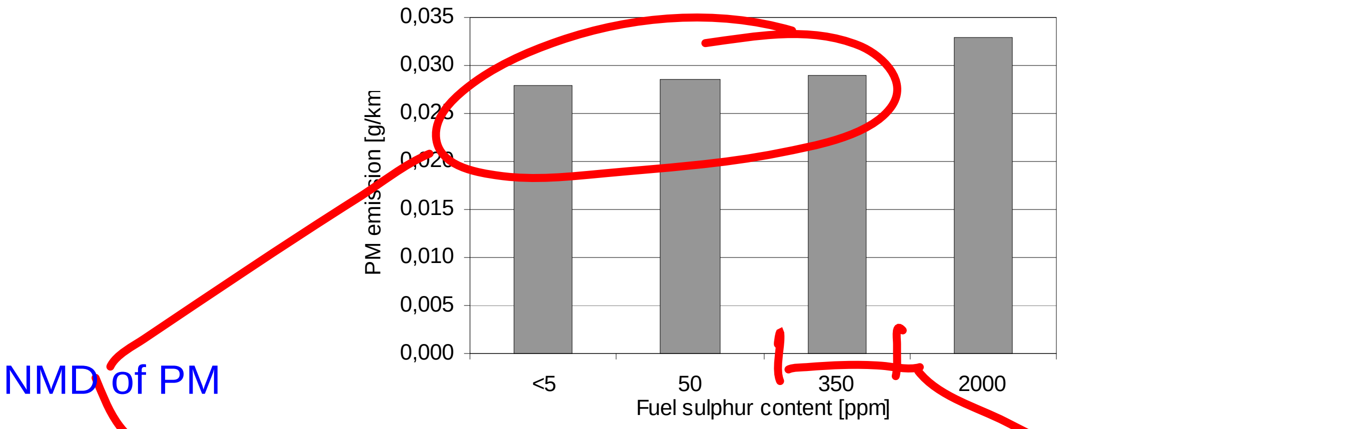

Fig. 7. *PM emissions during UDC as a function of diesel fuel sulphur content*

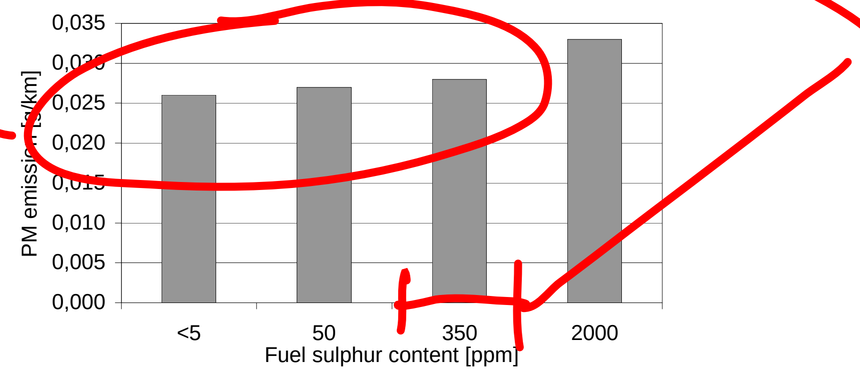

Fig. 8. *PM emissions during EUDC as a function of diesel fuel sulphur content*

When comparing the influence of the diesel oil sulphur content on the PM emissions in the stationary test ECE R-49 described in [2] and [13] and in the NEDC test performed on a chassis dynamometer, some distinct differences can be noticed. Considering, for example, the fuels with the sulphur content of 50 ppm and 2000 ppm the differences in the PM emissions in the ECE R-49 tests are close to 60%, whereas in the NEDC test it is lower than 20%. It should be obviously taken into account that the considered tests have been performed at the different test objects, however, in the authors' opinion this situation is determined mainly by the basically different procedures of both tests. The ECE R-49 test starts after warming the engine up to the nominal temperature. The engine load is definitely higher than during the test at the chassis dynamometer and reaches the full load value. These are the most favourable conditions for forming the sulphates. Moreover, the Mode Weighting Factors are highest for the full load phases.

The NEDC test, starting with the cold start mode, and lasting for a significantly shorter time and run at lower loads, creates significantly less favourable conditions for the formation of sulphates. This interpretation can be found in literature. Tamanouchi and co-writers [18] report on the significant differences of the sulphur influence on the PM emission in various tests: US Transient Mode Test and Japanese 13 Mode HD Test.

4. Conclusions

- ✔ The reduction of the sulphur content in fuel causes a reduction of PM emissions from a direct-injection common-rail diesel engine with oxidation catalyst during the NEDC test. However, this reduction is smaller than during the ECE R-49 test due to the less severe conditions of the test (cold start, lower load) presenting less favourable conditions for forming the sulphates.
- ✔ From two parts of the NEDC test the second part – the EUDC test – is more sensitive for the diesel fuel sulphur content. Within the EUDC test the catalyst reaches its nominal work temperature and the engine loads are higher.
- ✔ The influence of the diesel fuel sulphur content on the PM emissions significantly changes depending on the selected research test conditions.
- ✔ The fact that the reduction of the PM emissions by the reduction of the diesel fuel sulphur content is not accompanied by a increase of other regulated emission components and fuel consumption is of great importance.
- ✔ Although the PM reduction is less than could be achieved by the most modern engine technology or alternative fuels, the immediate net effect of fuel sulphur content reduction on the emissions is significant, since it takes place over the whole vehicle population.

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Abbreviations

CO_2 carbon dioxide
CVS constant volume sampling
CR common-rail
DI direct injection
E250 (E350) percentage v/v of a fuel distilled at 250°C (350°C)
EGR exhaust gas recirculation
EUDC Extra Urban Driving Cycle
FBP final boiling point

IARC	International Agency for Research on Cancer
IBP	initial boiling point
LEV	Low Emission Vehicles
NEDC	New European Driving Cycle
NO_x	nitrogen oxides
PM	particulate matter
SO_2	sulphur dioxide
SO_3	sulphur trioxide
SOF	soluble organic fraction
T50 (T90)	temperature at which 50 (90) % v/v of the fuel distills
UDC	Urban Driving Cycle
ULEV	Ultra Low Emission Vehicles