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ON-ROAD TEST EXHAUST EMISSIONS VEHICLE POWERED BY COMPRESSED NATURAL GAS

[1]Pielecha, Jacek (*); [1]Merkisz, Jerzy; [1]Labedz, Krystian
[1]Poznan University of Technology, Institute of Combustion Engines and Transport, Poland

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ABSTRACT – The paper presents results of the road tests of exhaust gas emissions of vehicles of different emission classes (Euro 4 and Euro 5, with different mileage), fuelled with compressed natural gas. The tests of exhaust emissions were conducted on parts of the road with different characteristics of the traffic intensity. For each phase of the tests, the characteristics of the test run and the value of exhaust gas emissions were determined. To measure the concentration of harmful substances, the Portable Emission Measurement System (PEMS) was used. The results were used to compare the vehicles and determine the emission indices, which subsequently were used to assess from ecological point of view the objects of tests in terms of emissions of toxic substances.

INTRODUCTION

Since the end of the last century might be observed an increase of interest of the leading automotive companies in factory-fitted CNG vehicles. It is caused by economic reasons, associated with lower prices of alternative fuels and the tax allowance schemes applied in some countries of Western Europe, as well as by the wish of the leading companies to include in their range of products vehicles fitted for this type of fuel. In case of Volkswagen concern, the serial production of CNG fueled vehicles started in 2006 with the introduction of Caddy and Touran Eco Fuel models. The model offered earlier – Golf IC Variant BiFuel – should be considered a low-volume production. Then, in 2010, Passat Eco Fuel 1.4 TSI was added to the CNG fueled range of vehicles, followed by Audi A3 TCNG in 2012. In recent months took place the world premiere of the smallest CNG fueled vehicle – VW Up, and the company is still planning to introduce into the market the latest generation of VW Golf fueled with compressed natural gas. Assuming that since the launch of Cady Eco Fuel model about 5,000 cars have been produced every year, it might be estimated that now about 35,000 vehicles of this model move about on the European roads (mainly in Germany). After analysis of these vehicles it has been observed that their mileages have been much higher compared to vehicles powered by conventional fuels. Quite frequently occur vehicles with average yearly mileages of about 75,000 – 90,000 km (e.g. taxi corporations, courier companies etc.). It is interesting though, that the volume of emission of harmful substances from vehicles with higher mileages (of about 500,000 km) changes compared to the vehicles with much lower mileages.

THE AIM OF TESTS

The aim of the tests was to determine the effect of mileage of CNG fueled vehicles on emission of harmful substances in exhaust gases so that the results obtained allowed to define to what extent the mileage influences the ecological indices of a CNG fueled vehicle. The comparison was conducted on cars of the same model with mileages of 75,000 and 500,000 km respectively, and for cars of different emission classes.

TESTED OBJECTS

The objects tested were Volkswagen Caddy Eco Fuel cars. On the manufacturing stage that model is already fitted for fueling with compressed natural gas (CNG), which constitutes its basic fuel. Gasoline is used only in emergency and for this reason the volume of the gasoline tank has been limited to 12 dm^3. CNG is stored in four steel pressure vessels which can accommodate about 26 kg of CNG in total, which allows for travelling the distance of 400 to 440 km.
Compressed natural gas is supplied by valves on vessels and gas hoses to the gas pressure regulator located in the engine compartment where the gas pressure is reduced from over 20 MPa to a range from 0.44 to 0.55 MPa. From the pressure regulator the gas is directed to the pressure reservoir from where through gas injectors it is supplied to the inlet manifold.
The cars used in tests, since their introduction into the market in 2006, have complied with the exhaust gas emission requirements set up in Euro 4 standard in force at that time. After minor modifications of the engine

control software in 2009, VW Caddy Eco Fuel vehicles have been type-approved according to Euro 5 standard. In both versions they have been equipped with the same type of three-way catalyst (TWC).
The tested vehicles were different in terms of the year of production (emission class) and total mileage (Table 1). However, technically the models were similar (equipment, engine parameters etc.).

Table 1: Specification of the tested vehicles.

Parameter	Euro 4	Euro 5
Year of production	2008	2009
Total mileage [km]	75,000 and 500,000	75,000 and 500,000

METHODOLOGY OF TESTS

Measurements of toxicity of exhaust gases have been conducted in different driving conditions. Based on [1, 5, 6, 7], the test route combined elements of driving in urban conditions – the city centre – and out of the city conditions as well as motorway conditions.
For the tests were used Volkswagen Caddy Eco Fuel cars with mileages of 75,000 and 500,000 km, belonging to different emission classes. The test runs were conducted twice for each phase of the research. The first phase including measurements of emission of gases and particulate matter, in which were used vehicles of Euro 4 emission class and different mileages, was conducted on the same day. The second phase – tests of vehicles of Euro 5 emission class – was conducted on the following day.
During the test runs efforts were made to maintain the same driving style to enable comparison of results of emission of toxic substances in exhaust gases. After processing the results twice and lack of any significant scatter of results (less than 2% compared to average value of estimated parameter) and due to similarity of the vehicles tested, for analysis were accepted results achieved for a particular test run (the first run). Detailed characteristics of the test runs are presented in Table 2. Differences in duration of test runs ensue from traffic intensity during the tests.

Table 2: Specification of the test for tested vehicles.

Test parameters	Characteristics			
Vehicle’s mileage	75,000 km		500,000 km	
Emission standard	Euro 4	Euro 5	Euro 4	Euro 5
Duration of test run [s]	3099	2363	2681	2265
V_{max} [km/h]	120	120	120	120
V_{avg} [km/h]	34.1	46.2	40	47.1
Length [km]	29.4	30.05	29.6	29.7
Time of the test run	16.15-17.06	11.02-11.41	14.34-15.18	10.30-11.09

For analysis of the concentration of harmful substances in exhaust gases was used the portable emission measurement system SEMTECH DS [2, 3, 4, 9]. It enabled measurement of harmful substances – CO, CO2, HC and NOx. For analysis of particle mass was used the portable analyser AVL 483 Micro Soot Sensor [8, 10]. Measurement of distribution of particle sizes was conducted with the use of the mass spectrometer 3090 EEPS from TSI Incorporated. Figure 1 presents the measuring scheme, and Figure 2 – a vehicle with installed apparatus for conducting tests in real traffic conditions.

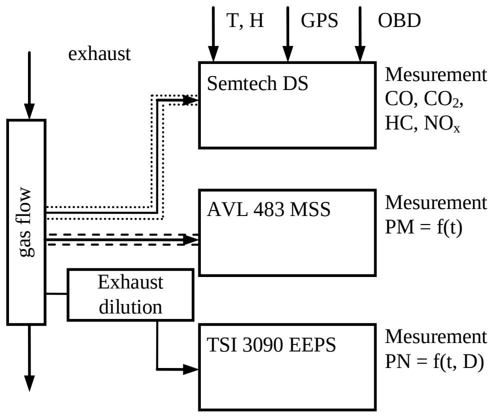

Figure 1: Connection diagram of measuring devices used in tests.

Figure 2: Vehicle with installed apparatus for measuring emission of exhaust gases in real traffic conditions.

TEST RESULTS

The analysis of driving conditions for all tested vehicles (Table 3) allowed for acceptance of the thesis that driving conditions of the vehicles were similar. On that basis the share of driving conditions was compared in terms of the following: acceleration of the vehicle, constant velocity, braking and stopping of the vehicle. Detailed analysis of the discussed operating statuses of the vehicle shows insignificant deviations from the average values of each investigated status. The biggest deviation from the average value does not exceed 2%.

Table 3: Characteristics of shares of driving conditions for tested vehicles.

Vehicle	Share of driving conditions			
	$V > 0, a > 0$	$V = const, V \neq 0$	$V > 0, a < 0$	$V = 0$ (stop)
Euro 4; 75,000 km	0.33	0.13	0.32	0.22
Euro 4; 500,000 km	0.34	0.16	0.31	0.19
Euro 5; 75,000 km	0.34	0.18	0.30	0.18
Euro 5; 500,000 km	0.33	0.17	0.30	0.20
Average	0.335	0.160	0.307	0.197
Average deviation	1%	2%	1%	1%

The recorded values of the intensity of emission of harmful substances in exhaust gases during the test are presented incrementally to reflect the total change of emission.

Emission of carbon dioxide for the tested vehicles is very similar for the whole range of the research test (Fig. 3a), which indicates similar level of fuel consumption and simultaneously proves lack of significant wear causing reduction of power and torque, and also proves that the operational parameters of the engine have been maintained.

Different results were recorded for emission of carbon monoxide (Fig. 3b) and nitric oxides (Fig. 3c). In case of the first substance, the vehicles with mileage of about 75,000 km show far smaller final values (approximately by 50%). Thorough analysis confirms, however, that increased emission of carbon monoxide for vehicles with higher mileage might be observed during the whole test (for high-mileage vehicles it is approximately twice higher compared to vehicles with mileage of 75,000 km, indicating independence of the traffic conditions).

Emission of nitric oxides for vehicles with mileage of 75,000 km amounts to about 10% of the value of emission for vehicles with mileage of 500,000 km, independent of the emission class of the vehicles. The sevenfold increase of the mileage of a vehicle causes increase of emission of nitric oxides by several times (Fig. 3c). It might be caused by very low efficiency of the catalytic converter in vehicles with such mileage.

While considering the emission of hydrocarbons it should be pointed out that for vehicles of Euro 4 emission class there is significant consistence in recorded data (Fig. 3d). Differences between these vehicles are unnoticeable (less than 5% in the whole tested range). For vehicles of Euro 5 emission class the difference amounts to 20% – by such value is increased emission of hydrocarbons with the increase of vehicle’s mileage from 75,000 to 500,000 km.

Emission of hydrocarbons form vehicles of Euro 4 emission class is lower than emission from vehicles from Euro 5 emission class, which might be explained by different characteristics of gas injection system or by negative changes in the gas supply system in vehicles of higher emission class.

Additionally – only for comparison purposes – the emission of particulate matter was measured for all tested vehicles (Fig. 3e). For vehicles with mileage of 75,000 km, emission of particulate matter throughout the test did not exceed 2 mg, while for the vehicles with mileage of 500,000 km the emission was several times higher. The nature of the increase was similar to the increase of road emission of carbon monoxide. It ensues from the reason of formation of those substances, which is deficiency of oxygen in the combustion chamber. Also the increases of those two substances are observed in similar moments, that is during rapid acceleration of the vehicle with stepwise increase of the fuel dosage.

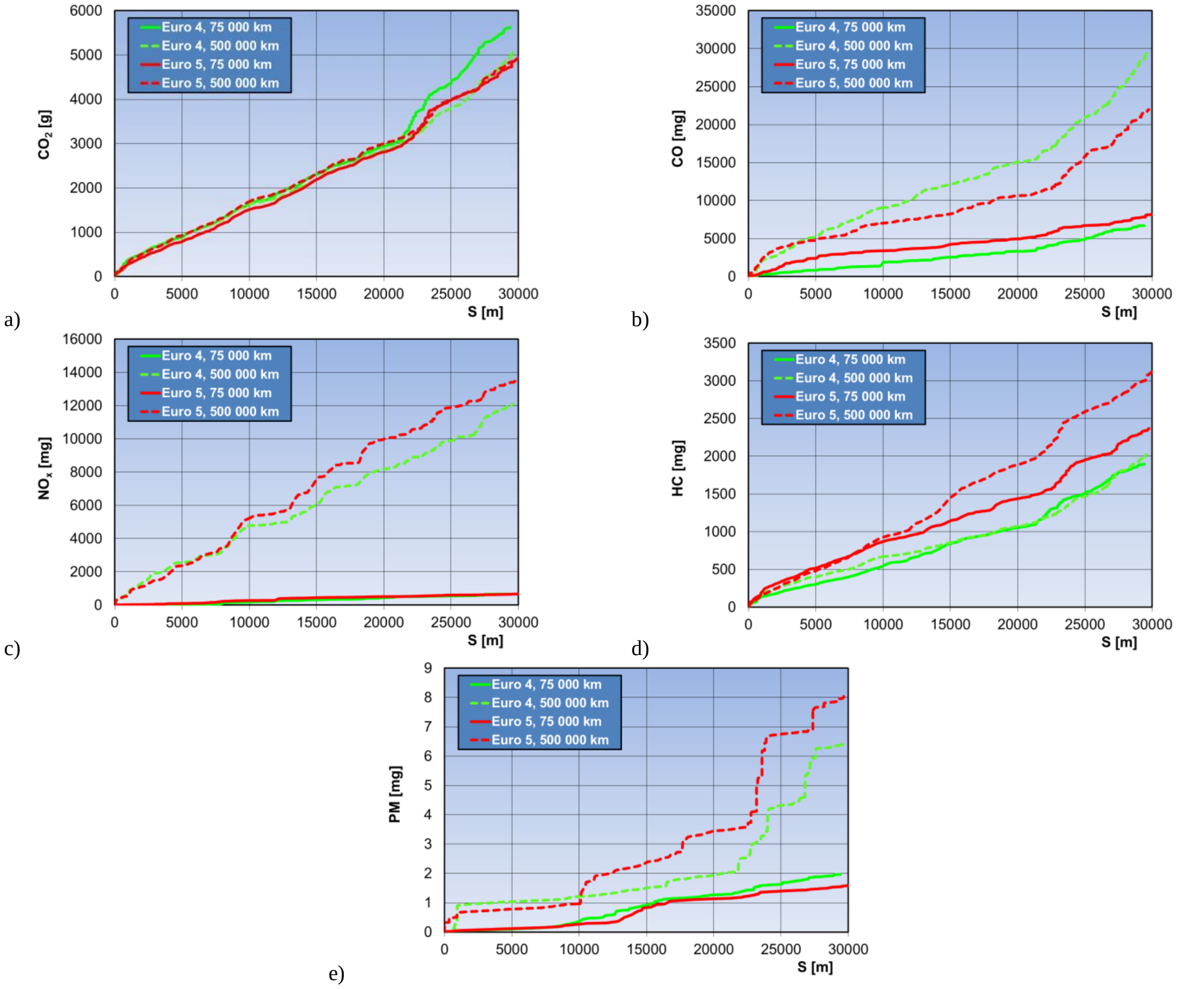

Figure 3: Characteristics of a) carbon dioxide, b) carbon dioxide, c) nitric oxides, d) hydrocarbons, e) particulate matter emission (incrementally) during the test for all tested vehicles.

ANALYSIS AND DISCUSSION OF THE RESULTS

The emission of carbon dioxide determined during tests is highest for vehicles with mileage of 75,000 km and emission class Euro 4 (Fig. 4). It is associated with the fact that this particular test run lasted the longest time, which means that during the test run fuel was consumed entirely. It might be therefore assumed, (assuming that the increase of carbon dioxide emission was caused by increased traffic), that there are no differences in the amount of carbon dioxide emission for vehicles with different mileage.

In the analysis of carbon monoxide emission (Fig. 5) might be observed significant influence of the vehicle's mileage on road emission of this substance, which proves to be several times higher for vehicles with mileage of 500,000 km. The seven-fold increase of vehicle's mileage in emission class Euro 4 causes approximately fivefold increase of road emission of carbon monoxide, while for vehicle of emission class Euro 5 this emission is increased about three times.

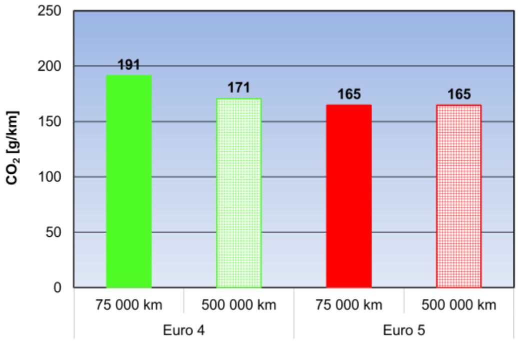

Figure 4: Comparison of road emission of carbon dioxide for vehicles with different mileage and emission classes Euro 4 and Euro 5.

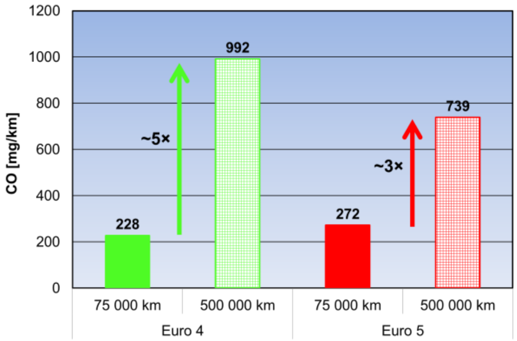

Figure 5: Comparison of road emission of carbon monoxide for vehicles with different mileage and emission classes Euro 4 and Euro 5.

The tested vehicles with higher mileage emitted about 1.2–1.5 times more hydrocarbons compared to the vehicles with mileage of 75,000 km (Fig. 6). However, between the vehicles with similar mileage a significant consistence of results might be observed: for the vehicles with mileage of 75,000 km the deviation amounted to a few percent for vehicles from different emission classes, while for vehicles with mileage of 500,000 km the deviation amounted to 24%.

The biggest influence of the vehicles' mileage on their ecological parameters was observed for measurements of road emissions of nitric oxides (Fig. 7). For vehicles of Euro 4 emission class the increase of mileage caused eighteen-fold increase of nitric oxides emission, and for vehicles of Euro 5 emission class the increase was twenty-fold. Also worth noting are similar values of road emissions of nitric oxides obtained for vehicles from different emission classes.

Significant is the influence of the vehicle's mileage on the value of road emission of particulate matter – in relation to the particle mass (Fig. 8). The values obtained for the vehicles from different emission classes and with mileage of 500,000 km are about 3 to 5 times bigger compared to the vehicles with mileage of 75,000 km. It indicates considerable wear of supply systems (mainly injectors) and imprecise fuel dosage in transient conditions of the engine. More significant changes for vehicles of Euro 5 emission class confirm the obtained bigger changes in road emissions of hydrocarbons.

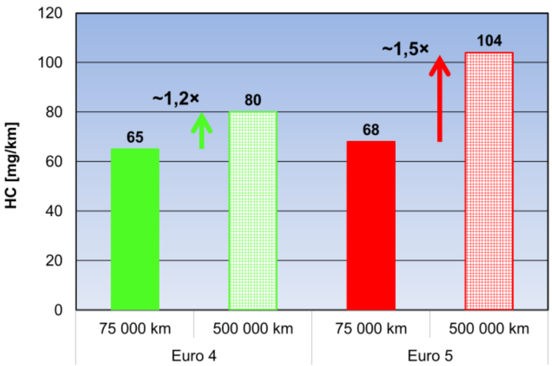

Figure 6: Comparison of road emission of hydrocarbons for vehicles with different mileage and emission classes Euro 4and Euro 5.

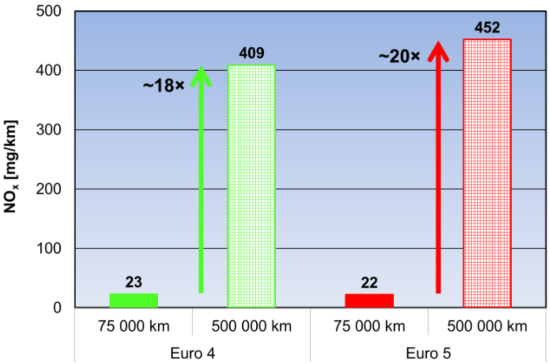

Figure 7: Comparison of road emission of nitric oxides for vehicles with different mileage and emission classes Euro 4 and Euro 5.

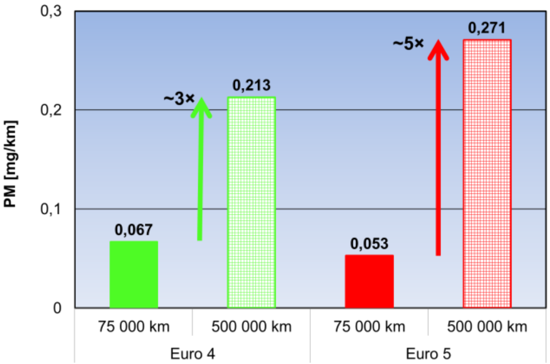

Figure 8: Comparison of road emission of particulate matter (in relation to the particle mass) for vehicles with different mileage and emission classes Euro 4 and Euro 5.

The tested vehicles, even those with mileage of 500,000 km, did not exceed the acceptable limits for carbon monoxide and hydrocarbons emissions (Table 4). The exception here is just the road emission of nitric oxides, which for the above mileage is exceeded five times – for vehicle of Euro 4 emission class, and seven and a half times – for vehicles of Euro 5 emission class. This might indicate that just minor changes were introduced in vehicles of Euro 4 class to meet the requirement of the higher standard. Such a conclusion might be also made after the analysis of acceptable limits of exhaust gases emissions for vehicles meeting requirements of Euro 4 and Euro 5 standards.

Table 4: Acceptable values of exhaust emissions in mg/kg according to Euro 4 and Euro 5 standards for vehicles with spark-ignition engines.

Exhaust emission	Euro 4	Euro 5
CO	1000	1000
HC	100	100
NOx	80	60
PM	–	5*
* for vehicles with SI engines and direct fuel injection.		

DIMENSIONAL CHARACTERISTICS OF PARTICULATE MATTER EMISSION

The dimensional characteristics of particulate matter emission (in relation to particle number) was calculated for the entire test – as the average value of the whole measured route and of the selected parts of the test run with constant speed on the motorway. The speed selected was 120 km/h. For that speed was determined the dimensional distribution of particle number in relation to particle's diameter. In accordance with the requirements of standard concerning measurements of the number of particles emitted from cars' engines [ALV, 2010; Pielecha, 2013] – the considered range inclued particles with diameter of 23 nm. To explain this issue precisely, in Figure 9 is presented dimensional distribution of particle number in relation to measuring diameter for vehicles with different mileage (averaged value for the whole measured route). The analysis of diagrams allows for conclusion that for vehicles of Euro 4/Euro 5 emission classes and with the mileage of 75,000 km the characteristic diameter of particles (the diameter of the biggest number of particles) is from 30 to 40 nm (Fig. 9a and 9c), while for vehicles with the mileage of 500,000 km, independent of the emission class, the range was shifted to the right (Fig. 9b and 9d) – to bigger diameters (35 to 60 nm).

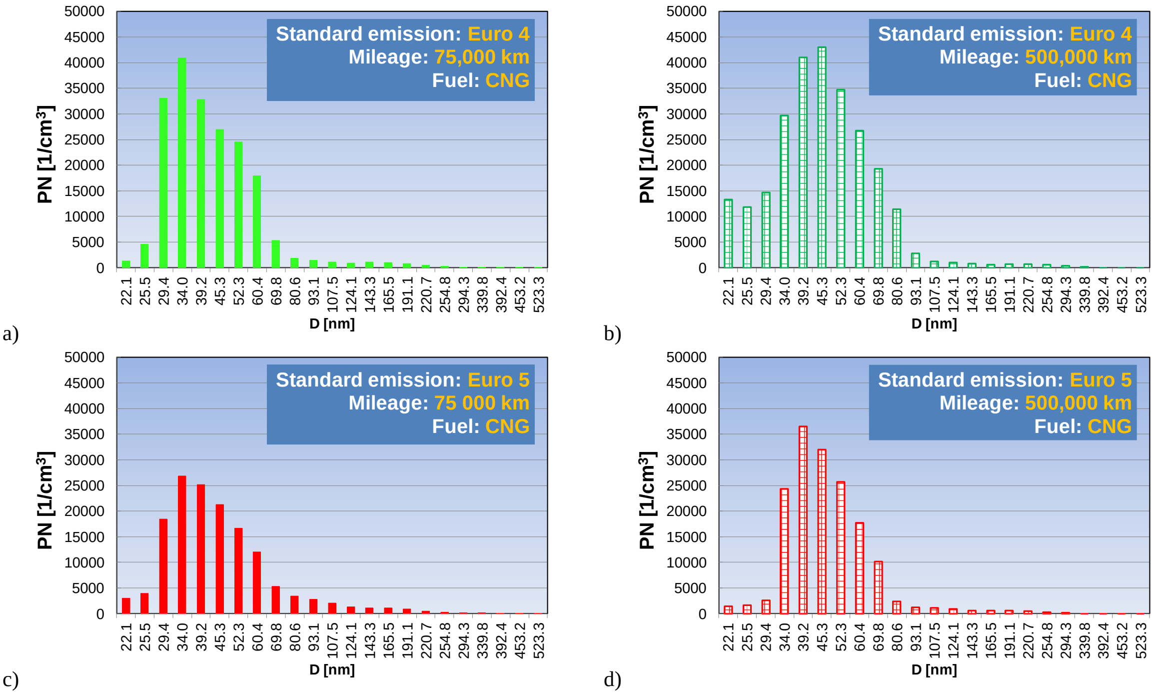

Figure 9: Detailed characteristics of the averaged particle number for the entire test run (vehicles with different mileage and different emission class) for: a) Euro 4 class and 75,000 km, b) Euro 4 class and 500,000 km, c) Euro 5 class and 75,000 km, d) Euro 5 class and 500,000 km.

Also the particle number is characteristic – it is almost invariable for vehicles of Euro 4 emission class – only the shift of sizes in the direction of bigger diameters occurs, while the distribution stays the same (the number of bigger particles for bigger mileages increases insignificantly). For the vehicles of Euro 5 emission class the total number of particles increases – and simultaneously there is an increase in their diameters. The reason might be the technical condition of the injection system, which was also confirmed in the earlier discussed results of the test of gaseous components.

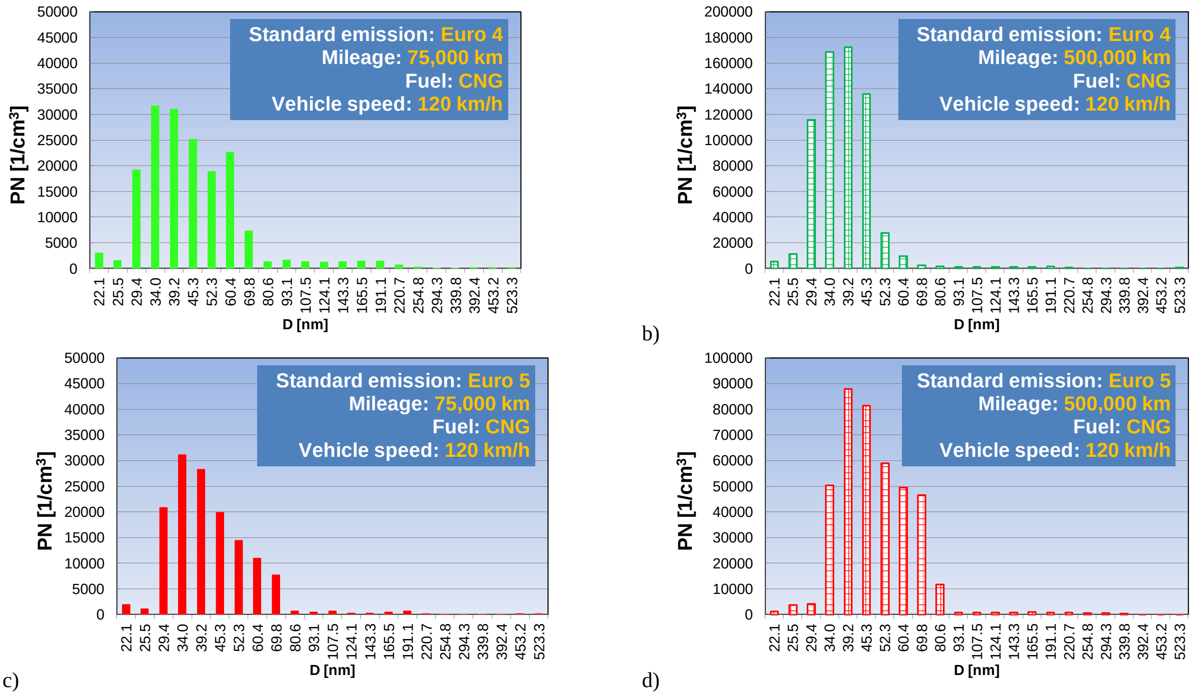

Figure 10: Detailed Dimensional characteristics of particle number for driving speed of 120 km/h (vehicles with different mileage and different emission class) for: a) Euro 4 class and 75,000 km, b) Euro 4 class and 500,000 km, c) Euro class and 75,000 km, d) Euro 5 class and 500,000 km.

The research in dimensional distribution was also repeated for the selected – constant – driving speed. As the maximum speed achieved in the test was 120 km/h, that value was selected for comparison (Fig. 10). The comparison of vehicles of Euro 4 emission class with different mileages shows changes in the emitted particle number for significant engine loads. The vehicles of Euro 4 emission class and with significant mileage in such conditions emit approximately six times more of the particles in size 30 to 50 nm compared to vehicles with mileage of 75,000 km (Fig. 10a and 10c). The situation is similar for vehicles of Euro 5 emission class: the increase of mileage results in approximately three-fold increase of particles number; however – which is not consistent in the tested vehicles – in this case are formed more particles with bigger sizes (Fig. 10b and 10d). As a result the particle number increases by 50% compared to vehicles of Euro 4 emission class, but due to their bigger sizes the particle mass is increased even more, which was proved earlier.

CONCLUSIONS

After analysis of the emission of harmful substances it might be concluded that the mileage of vehicles has no significant influence on the quantity of emission of carbon dioxide and hydrocarbons. A significant increase, however, is observed for the emission of nitric oxides (approximately twenty-fold increase) and for carbon monoxide (about three- to five-fold increase). Undoubtedly, it is associated with wear of the catalytic converter. At the same time, the changes in quantity of emission of harmful substances from vehicles with the same mileage but different emission classes (Euro 4 and Euro 5) are almost unnoticeable.

On the basis of the analysis of the results of emission for a vehicle with 75,000 km mileage it might be observed that, independent of the emission class of the vehicle, the requirements of Euro 5 emission standard are fulfilled. What it means is that, in this respect, the manufacturer did not have to introduce any changes influencing the quantity of emission of harmful substances.

The increase of mileage of vehicles to 500,000 km also does not pose any major problems in terms of compliance with the harmful substances emission standard (excluding the road emission of NOx – it should be remembered, however, that the type-approval test is conducted from the cold start so in conditions, in which the least quantity of nitric oxides is produced – which might explain the difference).

As a supplemental phase for the conducted test it is recommenced to replace the catalytic converter – which is probably the most exploited component – in the tested vehicles and repeat the road tests. Such a supplemental phase could answer the question whether it is possible to gain any significant ecological benefits in vehicles fueled with natural gas.

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