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FUEL IMPACT ON EMISSIONS OF HARMFUL COMPONENTS OF THE EXHAUST GAS FROM THE CI ENGINE DURING COLD START-UP

WPŁYW PALIWA NA EMISJĘ SZKODLIWYCH SKŁADNIKÓW SPALIN SILNIKA O ZAPŁONIE SAMOCZYNNYM PODCZAS ZIMNEGO ROZRUCHU*

The paper presents the results of tests on the compression ignition PEUGEOT 2.0 HDI engine. It was fuelled by commercial diesel oil, B50 blend (50 % diesel oil and 50 % rapeseed oil fatty acid methyl esters), and blend of diesel oil and 5% EKO-V fuel additive manufactured by the INWEX company. The tests were conducted for cold and hot engine. When the engine started up from cold, the temperature of the coolant and lubricating oil was equal to the ambient temperature. In hot engine start-up, the temperature of the engine oil and the coolant was 90 ºC. The values of concentrations of the exhaust gas harmful components were measured before the catalytic converter.

Keywords: *diesel engine, engine start-up, biofuel, exhaust emission.*

W artykule przedstawiono wyniki badań silnika o zapłonie samoczynnym PEUGEOT 2.0 HDI zasilanego handlowym olejem napędowym, mieszaniną B50 (50 % oleju napędowego i 50 % estrów metylowych kwasów tłuszczowych oleju rzepakowego) i oleju napędowego z dodatkiem 5% preparatu EKO-V firmy INWEX. Badania wykonano dla zimnego i rozgrzanego silnika. Podczas rozruchu zimnego silnika temperatura cieczy chłodzącej i oleju smarnego była równa temperaturze otoczenia, natomiast podczas rozruchu silnika ciepłego temperatura oleju silnikowego i cieczy chłodzącej wynosiła 90ºC. Wartości stężeń szkodliwych składników spalin zmierzono przed katalizatorem utleniającym zainstalowanym w układzie wydechowym silnika.

Słowa kluczowe: *silnik o zapłonie samoczynnym, rozruch silnika, biopaliwo, emisja spalin.*

1. Introduction

Rapid development of the motor industry, observed in recent years, has led to search for new fuels to power internal combustion piston engines. Many national research centres have conducted tests on engines running on biofuels derived from different plants [1, 2, 3, 12, 13, 14, 17, 26, 27]. Engine fuelling by biofuels has many advantages. Biofuels are completely biodegradable, they allow reduction in the exhaust emissions of carbon monoxide, hydrocarbons and particulate matter [12, 25]. The research has also concerned the effect produced by adding plant oil fatty acid methyl and ethyl esters to diesel oils on the emissions of the exhaust gas harmful components during the CI engine cold start-up [8, 16, 19, 23, 28, 29]. In papers [4, 5, 7, 9, 15, 20, 21], it is stated that in the first stage of the cold engine start-up, the emissions of carbon monoxide, hydrocarbons and particulate matter are higher than those for the warm engine start-up. In addition to increased emissions of the exhaust gas harmful components, other negative phenomena may occur in the cold start-up. Those will be related to a higher level of vibration, noise, and the engine uneven running [9, 10]. The phenomena can be attributed to unfavourable conditions in the cylinder during the ignition of air-fuel mixture, e.g. worse fuel spray and vaporization of the injected fuel droplets. Auto-ignition delay period is affected by many factors, including, among others, the working medium temperature, fuel physical and chemical properties, fuel injection and cylinder air-filling profiles. In the regular engine operation, combustion is more complete when compared with cold engine.

The paper presents problems related to the cold start-up of internal combustion piston engine with compression ignition. The engine was fuelled by commercial diesel oil, diesel oil/ rapeseed oil fatty acid methyl esters blend B50 (50% of commercial diesel oil and 50% of rapeseed oil fatty acid methyl esters), and also by commercial diesel oil with EKO-V additive developed by the INVEX company (95% of commercial diesel oil + 5% of EKO-V additive). The tests were intended to assess the impact of the fuels listed above on the emissions of the exhaust gas toxic components. In the compression ignition engine, the combustion is preceded by auto-ignition delay period. It is a very important time interval, in which fuel injection occurs and fuel undergoes physical and chemical changes that constitute the so-called pre-flame reactions.

The properties of the fuel injected into the cylinder considerably affect the start-up duration and reliability, and also the engine reaching thermal balance. Fuel surface tension is of major importance as it influences the quality of the fuel spray. Other physical and chemical fuel properties also affect the fuel spray quality. The ignition delay period also depends on the temperature of the working medium in the cylinder. For a cold start-up, auto-ignition delay is longer, which results primarily from a longer time of fuel vaporisation, leading to an extension of the physical part of auto-ignition delay. Chemical part of ignition delay also has a significant effect on auto-ignition delay. According to [18, 22], at a lower temperature of the working medium, the chemical part of ignition delay is prolonged because the speed of chemical reactions decreases much faster than the speed of physical transformations occurring during that time. At high temperatures in

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** the cylinder, the speed of chemical reactions is high. Consequently, the auto-ignition delay period is determined by physical processes, such as speed of injection, fuel vaporization and air/fuel vapour mixing. Fuels with higher cetane number have better auto-ignition properties and are characterised by shorter auto-ignition delay periods.

Cold engine start-up and emissions of the exhaust gas toxic components depend on physical and chemical properties of fuels. Those include the following: cetene number, distillation point of a specified fuel portion, viscosity, density, surface tension, cold filter plugging point and freezing temperature. Fuel for compression ignition engines should have high vaporization capacity. Fuels characterised by lower distillation point of a fuel fraction allow easier engine start-up, especially at low ambient temperatures. Fuels with a higher cetane number provide for easier engine start-up.

When the engine starts from cold, the exhaust gas contains more unburnt hydrocarbons, fuel vapours and incomplete combustion products [5, 6]. One of interesting solutions aimed at lowering the concentrations of the exhaust gas toxic components during the start of the cold engine is a short start-up without delivering fuel to the engine, which causes the pre-heating of the combustion chamber due to compression. As a result, lower concentrations of carbon monoxide, hydrocarbons and particulates are obtained [15]. During the cold start-up of the engine equipped with the exhaust gas recirculation system, some of the gas returns to the engine and can shorten the auto-ignition delay period [11]. Due to stricter standards on concentrations in the exhaust gas from internal combustion piston engines, it is necessary to use alternative fuels that produce lower negative environmental impact. Following those trends, the paper investigated the effect of using FAME and eco-friendly EKO-V additive, manufactured by the INVEX company, in diesel oil blends. The tests were aimed at measuring concentrations of the exhaust gas basic components during the start-up of cold and warm engine.

2. The test object and the measurement stand

The test object was four-cylinder High Pressure Direct Injection (HDI) engine with the Common Rail system and the exhaust gas recirculation system. The specifications of the engine developed by PSA Peugeot Citroën are presented in Table 1.

Table 1. The engine specifications

PEUGEOT compression ignition engine, engine code: DW10TD		
Parameter	Unit	Value
Cylinder arrangement	-	in-line
Number of cylinders	-	4
Injection type	-	direct
Compression ratio	-	17.6
Cylinder bore	mm	85
Piston travel	mm	88
Engine cubic capacity	dm^3	1997
Maximum engine power	kW	66
Rotational speed at maximum power	rpm	4000
Maximum engine torque	Nm	209
Rotational speed at maximum torque	rpm	1900
Engine idling speed	rpm	800

The test stand was equipped with the KTS 540 diagnostic tester, the fuel flow meter made by the AUTOMEX company and the AVL exhaust gas analyser which allows measurements of nitrogen oxide, hydrocarbon, carbon monoxide and carbon dioxide concentrations. After the cold and warm start-up, the engine operated at idle speed for 120 s. In accordance with [30], the cold engine start-up was assumed to occur when the engine temperature was equal to the ambient temperature, i.e. 15°C. The warm engine start-up was assumed to be that when the temperature of the lubricating oil was 90°C. In the tests, the engine ran on commercial diesel oil, B50 blend and diesel oil with 5% eco-friendly, multi-purpose EKO-V additive developed by the INVEX company. The additive characteristics were given in study [24]. According to the manufacturer's info, the additive facilitates the engine start-up and reduces the fuel consumption.

Investigations into physical and chemical properties of fuels on which the engine ran were performed using used the ERASPEC-FTIR oil analyser by Eeralytics company. The results of investigations are presented in Table 2.

Table 2. Physico-chemical properties of the examined fuels

Parameter	Ekodiesel Ultra D diesel oil	B50 fuel	Diesel oil with 5% EKO-V content
Cetane number	52.4	50.8	55,5
Cetane index	52.8	51.4	58.2
Density at 15ºC, kg/m3	0.832	0.8535	0.8341
Amount of aromatic hydrocarbons, % (V/V)	24.2	23.0	20.7
FAME content, % (V/V)	7.28	53.4	6.02
Distillation point, T10, °C	214.3	246.5	221.4
Distillation point, T50, °C	280.4	336.2	286.2
Distillation point, T90, °C	342.7	369.7	336.3
Distillation point, T95, °C	355.1	371.3	346.2
Final boiling point, °C	372.2	384.9	392.0

Taking into account a significant effect of fractional composition of the fuel on its vaporization capacity, thus on its start-up properties, the measurements of 10, 50, 90 and 95% (V/V) distillation points of the fuels were taken. The results presented in Table 2 indicate that 50% content of rapeseed oil fatty acid methyl esters in diesel oil/ FAME blends produces an unfavourable effect the fuel start-up properties as T10, T50, T90 and T95 distillation points are higher when compared with those for neat diesel oil. It should be noted that the lowest T10 distillation point, equal to 214.3°C, was obtained for diesel oil. The lowest values of T90 and T95 distillation points were found for diesel oil with 5% EKO-V additive.

3. Experimental results

The experimental investigations into the PEUGEOT 2.0 HDI engine involved measurements of crankshaft rotational speed during cold and warm engine start-up. The measurements also included concentrations of: nitrogen oxides (NO_X), hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2). In the tests, the engine operated at the factory settings and was fuelled by the following: commercial diesel oil, B50 rapeseed oil fatty acid methyl esters (50%) / diesel oil (50%) blend, and diesel oil with 5% EKO-V fuel additive developed by the INWEX company.

The graph shown in Fig. 1 indicates that during the first stage of the start-up, the crankshaft rotational speed increased rapidly to approx. 870 rpm, which was followed by a decrease to approx. 730 rpm. Then after about 10 s, the crankshaft rotational speed stabilised at roughly 800 rpm, which corresponds to the engine idling speed.

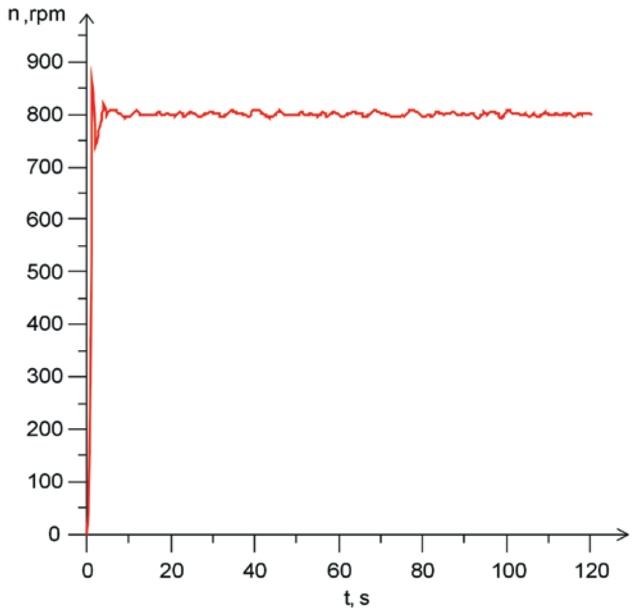

Fig. 1. Profile of crankshaft rotational speed during the cold start-up for Peugeot 2.0 HDI engine fuelled by diesel oil

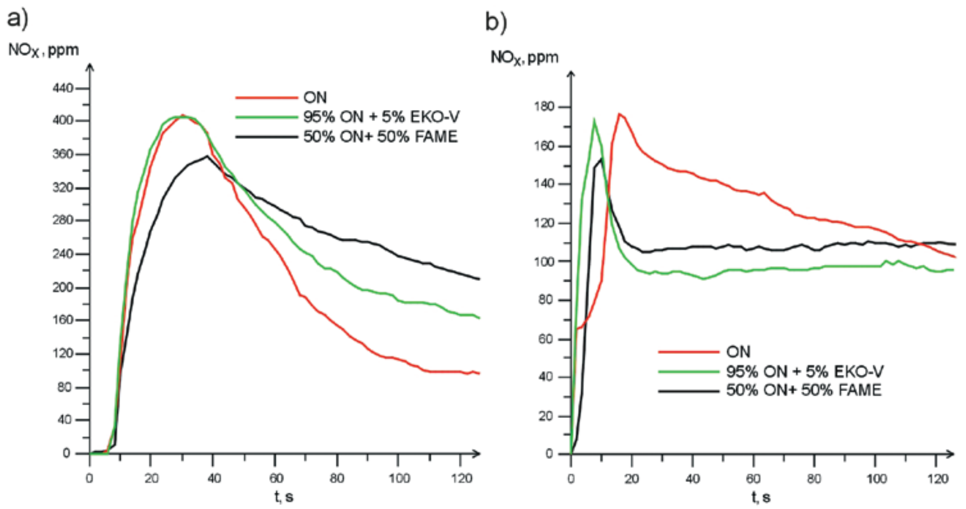

Fig. 2. Profile of nitrogen oxide concentrations in the exhaust gas from the Peugeot 2.0 HDI engine running on three fuels during: a) cold engine start-up; b) warm engine start-up

In Fig. 2, one can see graphs of nitrogen oxides concentrations during the cold and warm engine start-up for the engine running on three different fuels mentioned above.

The graphs presented in Fig. 2 indicate that during the initial stage of both the cold and warm engine start-ups, concentrations of nitrogen oxides increased rapidly. During the cold engine start-up, the maximum concentrations of nitrogen oxides were almost twice as high as those during the warm engine start-up. For cold and warm start-ups of the engine fuelled by B50 blend, the maximum values of nitrogen oxide concentrations were found to be lower. During the cold start-up of the engine fuelled by B50 blend, nitrogen oxide concentrations decreased more slowly when compared with two other fuels. During the warm start-up of the engine fuelled by B50 blend and by diesel oil with 5% eco-friendly EKO-V additive, after approx. 30 s from the start-up, values of nitrogen oxide concentrations stabilised at the level of 90÷110 ppm.

The analysis of the exhaust nitrogen oxide concentrations during the cold start-up, within the first operation stage of approx. 60 s following the start-up, demonstrates that for the engine fuelled by commercial diesel oil and by diesel oil with 5% EKO-V additive, concentrations of nitrogen oxides are twice higher when compared with the values measured 100 s after the engine start-up. Higher concentrations of nitrogen oxides during the cold start-up of the engine fuelled by B50 and by diesel oil with 5% EKO-V additive in comparison with neat diesel oil fuelling are found. That is caused by greater intensity of the combustion process, thus by higher in-cylinder temperature, resulting in a higher rate of nitrogen oxide formation. Greater intensity of the combustion process in the engine fuelled by B50 and by diesel oil with 5% EKO-V additive facilitates the engine reaching thermal balance, at which the emissions of nitrogen oxides stabilise. This stabilisation is primarily linked to the rate of the combustion of fuels on which the engine runs.

Fig. 3 shows the graphs of hydrocarbon concentrations during the cold and warm engine start-up for the Peugeot 2.0 HDI engine running on three different fuels mentioned above.

The analysis of graphs in Fig. 3 shows that during the initial stage of the cold engine start-up, hydrocarbon concentrations are lower than during the warm engine start-up. The reason may be a lower temperature of the combustion chamber walls, resulting in reduced vaporization intensity and vapour diffusion into air during the combustible mixture formation. Therefore, a greater amount of fuel mixes with the lubricating oil in the near-wall layer and flows to the engine crankcase. During the cold engine start-up, the lowest hydrocarbon concentrations were found when the engine was fuelled by B50. For the warm engine start-up, the highest hydrocarbon concentrations were observed for the engine fuelled by diesel oil with 5% EKO-V additive. A small increase in hydrocarbon concentrations during the warm start-up of the engine fuelled by commercial diesel oil with 5%

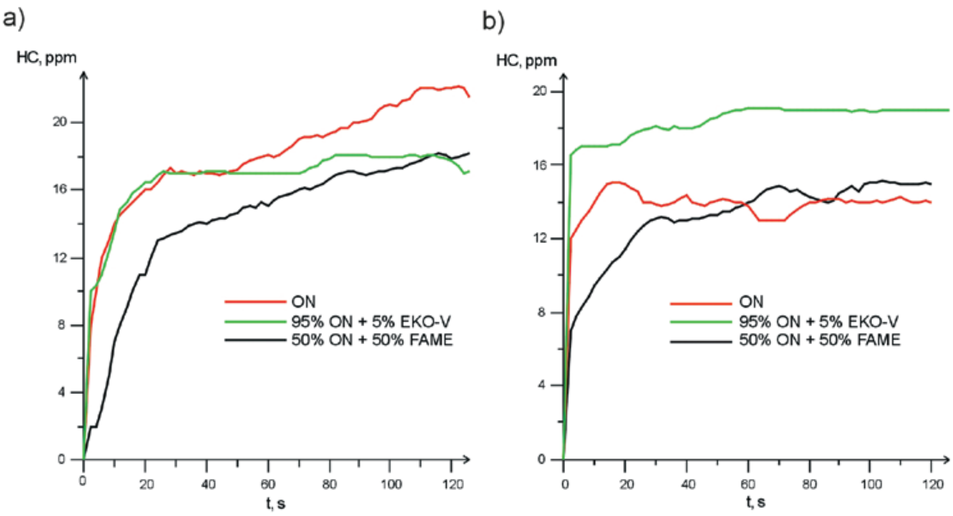

Fig. 3. Profile of hydrocarbon concentrations in the exhaust gas from the Peugeot 2.0 HDI engine running on three fuels during: a) cold engine start-up; b) warm engine start-up

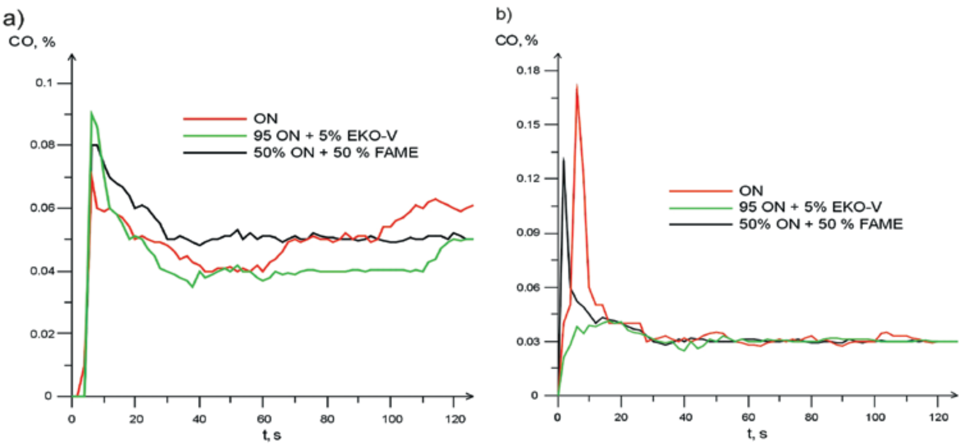

Fig. 4. Profile of carbon monoxide concentrations in the exhaust gas from the Peugeot 2.0 HDI engine running on three fuels during a) cold engine start-up; b) warm engine start-up

EKO-V additive and by B50 may be caused by the lowering of the temperature of the engine operating at idle speed. Increase in hydrocarbon concentrations during the cold engine start-up may be related to the incomplete combustion of the fuel injected into the cylinder. During the combustion process, the fuel-air mixture is not homogeneous and the mixture zones with different values of excess air coefficient are found.

The graphs illustrating carbon monoxide concentrations in the exhaust gas from the Peugeot 2.0 HDI engine running on the fuels selected for the tests can be seen in Fig. 4.

Carbon monoxide concentrations grew rapidly at the initial stage of the engine start-up. That referred both to the cold and warm engine start-ups for the engine fuelled by diesel oil and by B50 blend. For all fuels of concern, during the cold engine start-up, carbon monoxide concentrations stabilised after approx. 30 s. For the engine fuelled by commercial diesel oil with the EKO-V additive, during the cold start-up, the lowest carbon monoxide concentrations were observed after approx. 30 s of the engine operation. During the warm start-up of the engine running on diesel oil with the EKO-V additive, at the first stage of the start-up (up to approx. 15 s), the lowest carbon monoxide concentrations were found. The graphs shown in Fig. 4b indicate that during the warm start-up of the engine fuelled by diesel oil and by B50 blend, combustion was incomplete at the first stage of the engine operation (up to approx. 10 s), which led to increased emissions of carbon monoxide.

Fig. 5 presents carbon dioxide concentrations during cold and warm start-ups when the Peugeot 2.0 HDI engine was fuelled by the three fuels of concern.

Carbon dioxide concentrations stabilised within approx. 10 s after the cold and warm engine start-ups. Higher concentrations of carbon dioxide, which ranged 5.0÷5.6 %, were noted during the cold engine start-up. During the warm engine start-up, carbon dioxide concentrations ranged 3.8÷4.6 % after 10 s. For the cold start-up of the engine fuelled by commercial diesel oil, higher concentrations of carbon dioxide resulted from the combustion of a larger fuel charge delivered to the cylinder during the start-up.

4. Conclusions

On the basis of the analysis of the experimental results, the following conclusions can be drawn:

- the period of the cold engine start-up is characterised by high concentrations of nitrogen oxides,
- the use of rapeseed oil fatty acid methyl esters in blends with diesel oil results in lower concentrations of nitrogen oxides and hydrocarbons in the exhaust gas at the first stage of the cold engine start-up (up to 40 s after the start),
- concentrations of carbon monoxide and carbon dioxide during the cold engine start-up are higher when compared with the engine that is heated at the start-up,
- during the cold engine start-up, at the initial stage of the engine operation, a rapid increase in carbon monoxide and carbon dioxide concentrations in the exhaust gas is found,
- carbon monoxide and carbon dioxide concentrations in the exhaust gas during the engine start-up were comparable for the three fuels of concern,
- during the warm engine start-up, after approx. 20 s, the lowest concentrations of nitrogen oxides were noted for the engine fuelled by diesel oil with 5% eco-friendly EKO-V additive,
- during the warm engine start-up, the highest concentrations of hydrocarbons were observed for the engine fuelled by diesel oil with 5% eco-friendly EKO-V additive.

Summing up, it can be stated that the amounts of the exhaust gas toxic components during the cold engine start-up are much higher in comparison with those during the start-up of the pre-heated engine.

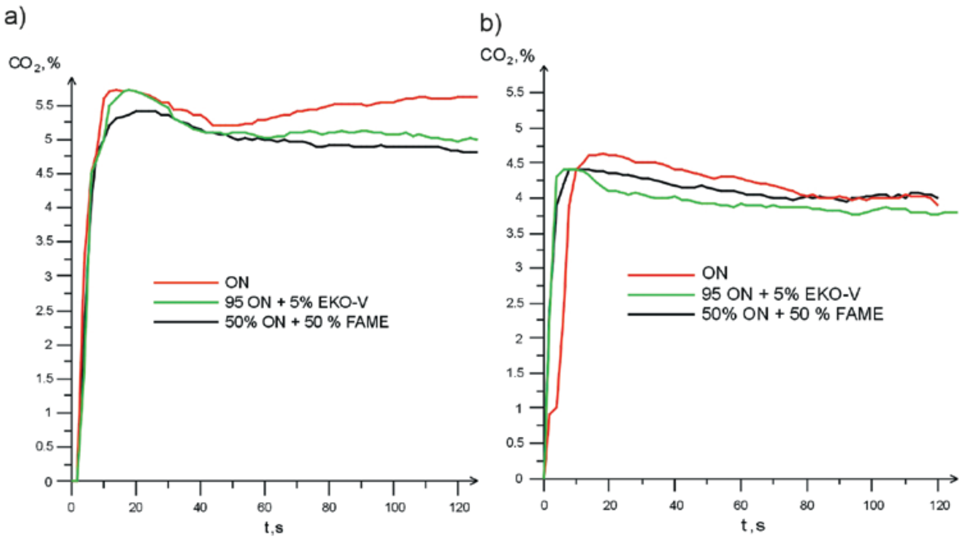

Fig. 5. Profile of carbon dioxide concentrations in the exhaust gas from the Peugeot 2.0 HDI engine running on three fuels during: a) cold engine start-up; b) warm engine start-up

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