

The impact of using an in-cylinder catalyst on the exhaust gas emission in real driving conditions tests of a Diesel engine

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Abstract. The article discusses the use of an in-cylinder catalyst, which allows the reduction of harmful exhaust compounds emissions during the internal combustion engine operation. It is a type of exhaust gas aftertreatment system – however, its placement in the combustion chamber – thus as close to the combustion process as possible, allows counteracting the production of pollutants at the source (catalyst applied on glow plugs). This is necessary because the reduction of exhaust emissions from vehicles is a key aspect of reducing the negative environmental impact of transport. The article presents the research results on the in-cylinder catalyst evaluation in dynamic operating conditions – the evaluation was made in road tests using the latest procedures recommended by the European Union. The presented comparative test results concern the road emission of limited vehicle exhaust compounds with the use of standard glow plugs and glow plugs with the catalytic layer applied. The use of an in-cylinder catalyst (on glow plugs) during diverse engine operating conditions results in a few percent reduction in the mass of carbon monoxide, hydrocarbons, carbon dioxide and the number of solid particles. The use of such a solution, technically possible to introduce quickly (replacement of a glow plug) in most vehicles with Diesel engines, would improve the overall ecological properties of internal combustion engines.

1. Introduction

Internal combustion engines will continue to dominate as the main power source of means of transport [1]. It has been predicted that in 2050 they will be used in 74% of drive systems, including increasingly popular hybrid systems. Due to the dynamic development of electric propulsion and hybrid systems, carbon dioxide emissions are expected to be reduced by 90% [2, 3, 4].

The increasing pressure to reduce the negative environmental impact of combustion vehicles, both from the legislative institutions of individual countries and their communities, forces the search for more and more sophisticated technical solutions for the internal combustion engine that will limit the above impact and enable meeting the current emission standards [5-8]. Among such solutions those that affect the mass of pollutants after leaving the combustion engine, i.e. the exhaust gas aftertreatment systems, are extremely important [9, 10]. Due to the specifics of such systems (obtaining high temperature of their operation, it is necessary to place these systems closer and closer to the engine) [11, 12]. However, these solutions are aimed at reducing the undesirable compounds that have already been generated (created) by the internal combustion engine [13-15]. On the other hand, one should carefully look at the solutions that are technically available, and which would reduce the generation of pollutants at the source – so namely in the combustion chamber itself – by placing catalysts as close as possible to the



combustion chamber. Hence the idea of combining processes in the cylinder with non-engine exhaust gas aftertreatment systems leading to the use of a catalyst inside the cylinder.

2. Literature review

The inspiration for undertaking this research was the work of Walkowiak and Janicka (the first in Poland, in which the catalytic coating was applied directly to the elements in the combustion chamber); as a result of their work, patents have been created (among others [16, 17]) as well as multiple publications, the results of which have been described, among others, in [18, 19].

Williams and Schmidt [20], analysing the ignition initiation parameters during studies on the catalytic oxidation of higher alkanes using rhodium as an active agent, noted that the introduction of a small amount of catalyst into the reactor simulating the conditions in the engine results in a reduction of emissions of these compounds. One of the authors' suggestions was that the active agent introduced into the combustion space causes initiation of chain reactions, at the same time shortening the time of chemical ignition delay.

Karuppasamy and Mageshkumar's research [21] concerned engine components coated with aluminum, titanium, nickel and chromium compounds applied through the plasma spraying method. The tests were carried out at constant rotational speed and variable load. The concentration of carbon monoxide, hydrocarbons and nitrogen oxides was determined and specific fuel consumption was determined for the following scope of research: head and piston crown elements without catalytic layer, head and piston crown elements coated with aluminum and titanium compounds (Al-Ti), head and piston crown elements covered with nickel and chromium compounds (Ni-Cr). Based on the obtained results, the authors of the article [21] stated that: there is no clear difference in the type of catalytic coverage on the value of carbon monoxide concentration in the exhaust gas; increase of hydrocarbon concentration in the exhaust gas in the majority of the tested load ranges up to 60%; in the case of the highest load, a decrease in hydrocarbon concentration by about 10% was noted; reduction of the concentration of nitrogen oxides in the exhaust gas in the whole engine load range by about 30%, which is extremely important in the case of diesel engine operation; reduction of the specific fuel consumption by about 15% in the whole range of the tested engine load.

The research by Soltic and Bach [22] concerned the issue of internal catalysts applied in a methane-fuelled spark ignition engine. The basis for conducting the analysis of the problem was the difficulty of methane reduction in the catalytic reactor due to the fact that it is the most molecularly stable hydrocarbon. Two pistons covered with different catalytic layers were tested: a platinum layer with a thickness of 20 nm, a porous layer of zirconium oxide with a thickness of $6 \cdot 10^5$ nm to increase the temperature of the catalytic surface, and thus the reactivity of the catalyst. As a result of the conducted research, the authors of the article [22] did not notice any significant changes in the concentration of nitrogen oxides in the exhaust gas, regardless of the fuel used and the excess air ratio. Similar results were reported in relation to the concentration of carbon monoxide in exhaust gases – no significant changes were observed regardless of the fuel used and the excess air ratio. The conclusion of the research was that the thermal and catalytic layers can withstand the thermal and mechanical loads occurring in the cylinder of the spark-ignition engine. A significant increase in the concentration of hydrocarbons in the exhaust gas was found due to the use of the piston cover with a catalytic layer. There were no changes in the concentration of other harmful compounds (nitrogen oxides and carbon monoxide).

The results of research on internal catalysts were also published in articles [23, 24], where a positive effect of catalytic coverage of some elements in the combustion chamber on the reduction of the carbon monoxide and hydrocarbons concentration has been shown, which unfortunately depends on the properties of the catalyst used and the operating conditions of the internal combustion engine. Such tests were carried out only in stable engine operating conditions, and in this dissertation an attempt was made to determine the ecological benefits of using an internal catalyst mainly in the dynamic conditions of the internal combustion engine operation as well as real operating conditions.

3. Research aim

Based on the literature data analysis, it can be concluded that modifying the engine combustion chamber, based on the introduction of an active agent (catalyst), can shorten the ignition delay by lowering the activation energy of the pre-ignition reactions, thereby improving engine performance and reducing the formation of harmful compounds in the engine cylinder. The catalyst located inside the combustion chamber can affect several stages of combustion of the fuel mixture in the combustion space of the engine: the preparation phase of the combustible mixture – injected fuel cracking processes, pre-flammable phase – shortening the ignition delay, combustion phase – combustion speed increase – combustion temperature increase (unfavourable increase in the concentration nitrogen oxides), post-combustion phase – combustion of hydrocarbons in the boundary layer and after-burning of carbon monoxide.

A unique methodology of testing the internal combustion engine in dynamic operating conditions was developed to achieve the research goal. Using the latest type approval recommendations, the methodology was developed and tests were carried out in real driving conditions (RDE tests), including the urban, rural and motorway sections.

4. Research methodology

4.1. Test object

The object of research and analysis were standard glow plugs (catalog number – 0250203002, trade abbreviation (HKB) – GLP016) and glow plugs covered with a ceramic layer. The application of ceramics onto glow plugs (done at Pratt & Whitney Rzeszow SA) was carried out according to the following sequence:

1. The sprayed element was first subjected to abrasive blasting using electro-corundum with a grain size of approx. $0.6\ \mu\text{m}$. The time between sandblasting and coating was less than 2-4 h, the surfaces were washed with a solvent.

2. The spray coating process was carried out in two stages:

- application of a base layer with a thickness of about $0.1\ \text{mm}$, using a nickel based powder for which the grain size was less than $100\ \mu\text{m}$, and hardness in the molten state was about 20 HRC;
- a ceramic layer with a thickness of about $0.1\ \text{mm}$, a ZrO_2 powder was applied, stabilized with yttrium (20% yttrium), with a grain size in the range of $40\text{--}60\ \mu\text{m}$; from a distance of about $100\ \text{mm}$, onto an element at $200\ ^\circ\text{C}$.

3. The spraying process was carried out using a plasma torch; the plasma power was about 15 kW for the base and 30 kW for the ceramic layer.

4. The surface of the layers was not sanded.

The layers obtained on glow plugs are shown in Figure 1.



Figure 1. Glow plugs with the ceramic coating layer.

4.2. Test vehicle

For performing the research a passenger car with a mileage of 92,000 km was used, with a charged 1.3 JTD (MultiJet) Diesel engine with a displacement of $1.3\ \text{dm}^3$, and Euro 4 emission class. The exhaust

after-treatment system was typical for Diesel engines with direct fuel injection common rail, i.e. a dual-function catalytic converter (a particulate filter was not required in vehicles of this emission category). The choice of such a research object was dictated by the fact that more than 50% of cars in the European Union are equipped with Diesel engines. But also, the Euro 4 emission standard was in force from January 1, 2006 to 2010, and the average age of imported cars to Poland is 11.5 years (of which 42% is with Diesel engines). Therefore, the most representative engine in Poland is the Diesel engine with the emission standard Euro 4.

4.3. Measuring equipment

Emission measurements were done in real driving conditions; this approach requires the installation of the gas sampling apparatus on the vehicle in such a way that ensures its normal operation. Therefore a gas sampling system was prepared, which together with the system measuring the flow rate of the exhaust gas also performed partial sampling of the flue gas for the analysers to enable making the measurement (Figure 2 shows the wiring schematic of the measuring equipment).

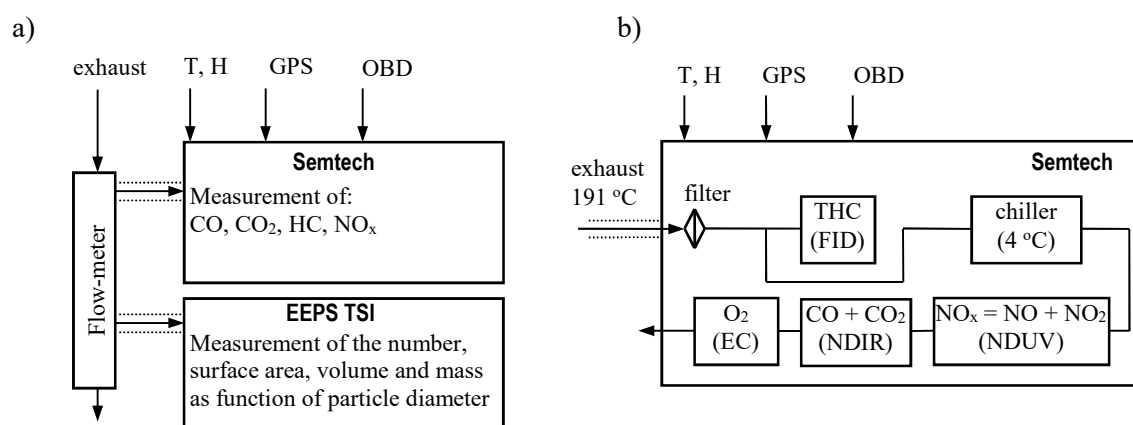


Figure 2. Diagram of the measurement system used for testing (a) and mobile exhaust gas analyser with marked flue gas flow (b) for the measurement of gaseous compounds and particulates; T – ambient temperature, H – air humidity.

For measuring the concentration of harmful substances in the exhaust gas the mobile Semtech DS Company Sensors (Sensors Emission Technology) analyser was used. It facilitated the measurement of exhaust emissions – carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides. Further data directly transmitted from the vehicle's diagnostic system was sent to the central unit of the analyser and a GPS was used. Information on the results from mobile gas analysers in conjunction with the data recorded with the on-board diagnostic systems confirms the desirability of taking the assessment of emissions in real traffic conditions with the use of the measuring apparatus.

4.4. Test route

As part of the harmful exhaust components emission tests in real driving conditions, the vehicle equipped with standard and modified glow plugs was tested. The aim of the tests was to determine the average values of road emissions of harmful compounds and the number of particles for each vehicle configuration, including urban, rural and motorway driving as well as the entire road test, in accordance with the requirements of EU 2016/247 [25] and EU 2016/646 [26]. The total length of the research route was approx. 75 km.

5. Results

5.1. Test routes comparison

Drives in the same vehicle with different configurations were characterized by a significant degree of similarity which was depicted in Figure 3. The speed profiles for two vehicles used in the tests were given: the first - with standard glow plugs and the second – with glow plugs covered with a catalyst.

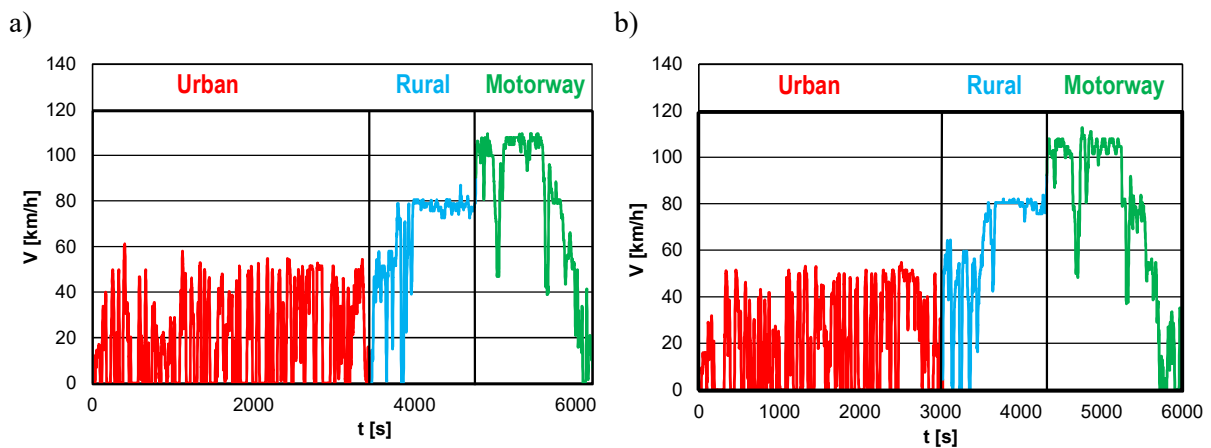


Figure 3. Speed profile in road tests for a vehicle powered with a Diesel engine: a) with standard glow plugs, b) with catalyst coated glow plugs.

Comparing the data in Figures 4 and 5, one can conclude similar driving dynamics for the two tests, where in extreme cases the values of parameters do not differ by more than 5%. This remark concerns both the RPA (Relative Positive Acceleration) and the 95th percentile of the product of velocity and positive acceleration ($(V \cdot a^+)[_{95}]$). In both cases, the data obtained for the urban, rural and motorway sections are comparable and, at the same time, fall within the permitted limits. Therefore, the criterion of research on the similarity of the drives, and thus the similarity of dynamic conditions, has been met.

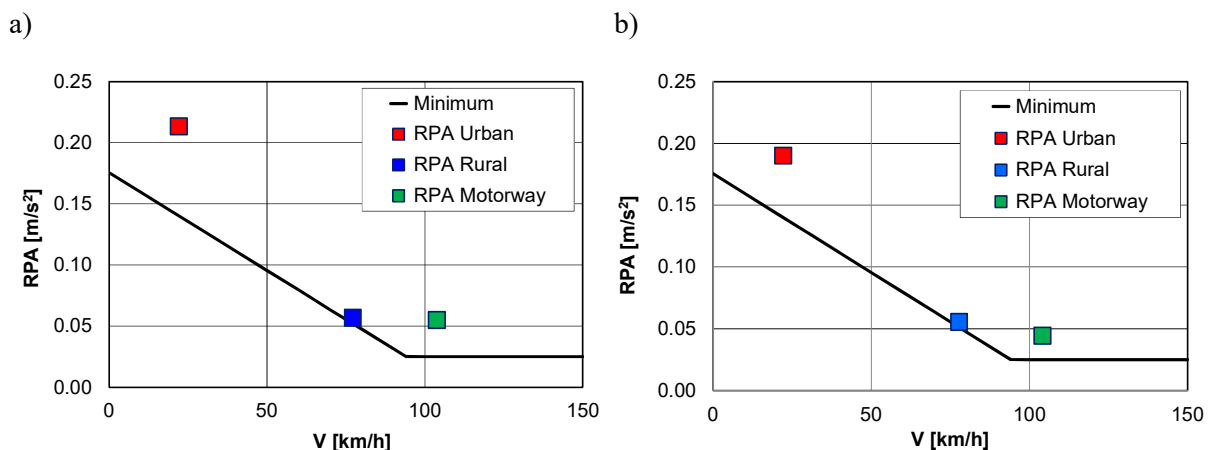


Figure 4. Comparison of dynamic motion parameters (relative positive acceleration) for a vehicle with a Diesel engine: a) with standard glow plugs, b) with catalyst coated glow plugs.

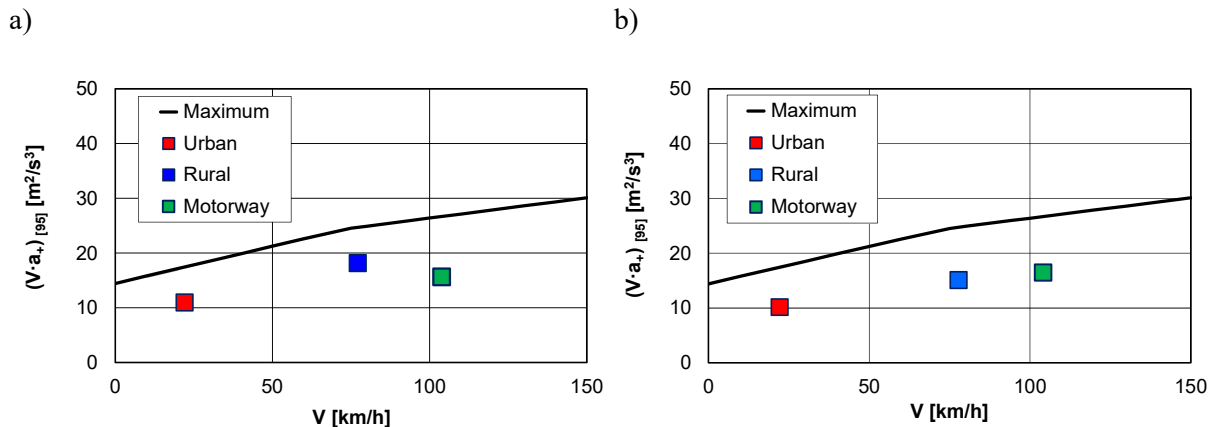


Figure 5. Comparison of dynamic motion parameters (95th percentile of the product of velocity and positive acceleration) for a vehicle with a Diesel engine: a) with standard glow plugs, b) with catalyst covered glow plugs.

The detailed characteristics of the drives are as follows:

- distance travelled differed by 90 m (relative difference 0.12%),
- travel time differed by 4 minutes (relative difference 3.85%),
- the share of the urban stage was different by 0.04%,
- the share of the rural stage differed by 1.43%,
- the share of the motorway stage differed by 1.47%,
- average speed in the urban section varied by 1.13 km/h (relative difference 4.79%),
- average speed in the rural section varied by 0.15 km/h (relative difference 0.19%),
- average speed in the motorway section varied by 1.13 km/h (relative difference 1.05%),
- the share of stationary in the urban section varied by 1.86%.

5.2. Road exhaust emissions

The carbon monoxide road emission from the tested vehicle was different in value depending on the considered stage of the vehicle's driving route (Fig. 6). However, it should be noted that the nature of the changes in road emissions of this compound in question converges for different glow plug configurations. Regardless of traffic conditions, this indicator was reduced. The highest values of road emissions of carbon monoxide were recorded in the case of vehicle drive in urban areas – the value of 2.35 g/km (for standard glow plugs) and 2.26 g/km (for catalytic-coated glow plugs) was obtained, as part of the rural section driving – 1.25 g/km (for standard glow plugs) and 1.20 g/km (for catalytic-coated glow plugs), as well as 0.85 g/km (for standard glow plugs) and 0.82 g/km (for catalytically coated glow plugs) for highway driving. The average road emission of carbon monoxide in the whole test was equal to 1.49 g/km for standard glow plugs and 1.43 g/km for catalytic-coated glow plugs. Throughout the test, the average value of carbon monoxide emissions reduction when using catalytic coated glow plugs was 4.03%.

In the case of hydrocarbon road emissions, the nature of its changes is very similar regardless of the considered stage of the vehicle's driving route (Fig. 7). The considered parameter was smaller for catalytic coated glow plugs at each stage of the journey. The highest values of hydrocarbon road emissions were recorded in the case of vehicle driving in the urban section – the value of 0.42 g/km (for standard glow plugs) and 0.39 g/km (for catalytic coated glow plugs) was obtained, in the urban driving stage – 0.21 g/km (for standard glow plugs) and 0.20 g/km (for catalytic coated glow plugs), and for the motorway driving stage – 0.11 g/km (for standard glow plugs) and 0.28 g/km (for catalytic-coated glow plugs). The average road emission of hydrocarbons in the whole test was equal to 0.30 g/km for standard

glow plugs and 0.28 g/km for catalytic-coated glow plugs. In the whole test, the average value of hydrocarbon road emissions reduction when using catalytic coated glow plugs was 6.67%.

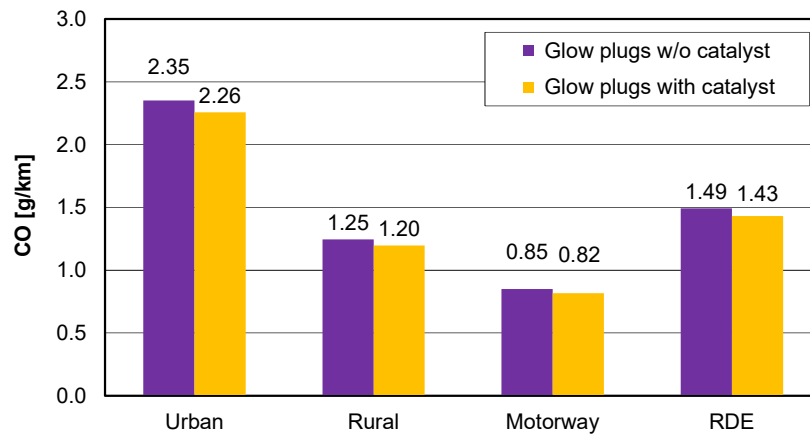


Figure 6. Carbon monoxide road emission in individual test stages and the entire test of a vehicle with a Diesel engine with standard glow plugs and catalyst coated glow plugs.

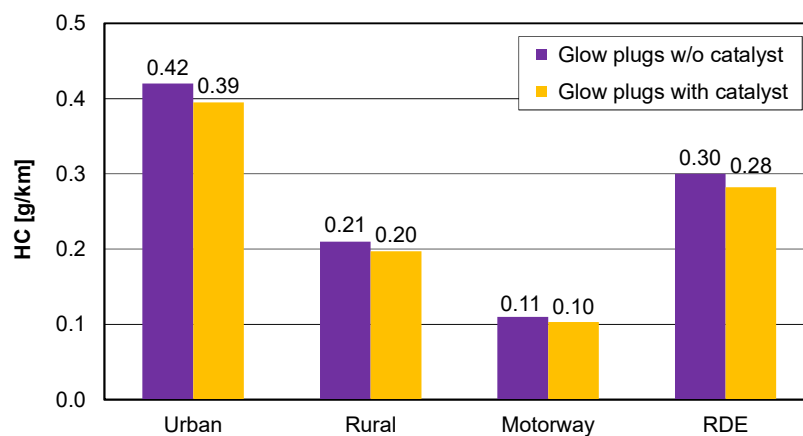


Figure 7. Hydrocarbon road emission in individual test stages and the entire test of a vehicle with a Diesel engine with standard glow plugs and catalyst coated glow plugs.

The nitrogen oxides emission from the tested vehicle varies depending on the considered stage of the vehicle's driving route (Fig. 8). It should be noted that the nature of changes in road emissions of the considered compound converges for different configurations of glow plugs – regardless of the traffic conditions, this value has been increased. The highest values of road emissions of nitrogen oxides were recorded in the case of driving the vehicle in urban areas, values of 0.87 g/km (for standard glow plugs) and 0.95 g/km (for catalytic coated glow plugs) were obtained, as part of the rural driving section – 0.39 g/km (for standard glow plugs) and 0.42 g/km (for catalytic-coated glow plugs), as well as 0.44 g/km (for standard glow plugs) and 0.48 g/km (for catalytically coated glow plugs) for the highway drive. The average road emission of nitrogen oxides in the whole test was equal to 0.57 g/km for standard glow plugs and 0.62 g/km for catalyst coated glow plugs. In the whole test, the average value increase of the nitrogen oxides road emissions with the use of catalytic-coated glow plugs was 8.8%.

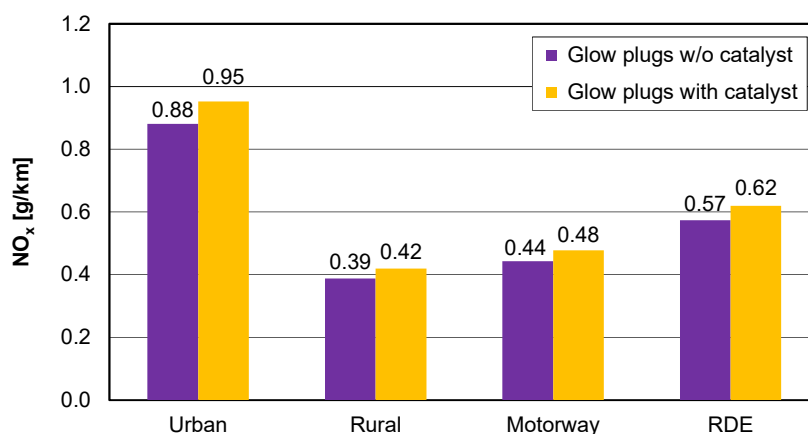


Figure 8. Road emission of nitrogen oxides in individual test stages and the entire test of a vehicle with a Diesel engine with standard glow plugs and with catalyst coated glow plugs.

In the case of road emissions of carbon dioxide (identical to the fuel consumption), the nature of its changes is unambiguous (except for one stage of research) depending on the considered stage of the vehicle's driving route (Figure 9). The highest values of road CO₂ emissions were recorded in the case of urban vehicle driving – the value of 187 g/km (using standard glow plugs) and 182 g/km (using catalytic-coated glow plugs) was obtained, in the rural driving stage – 85 g/km (with the use of both types of glow plugs), and during the motorway driving stage – 87 g/km (using standard glow plugs) and 86 g/km (with the use of catalytic coated glow plugs). The average carbon dioxide road emission in the whole test was equal to 123 g/km (standard glow plugs) and 120 g/km for catalytic-coated glow plugs. In the whole test, the average carbon dioxide emission value reduction when using catalytic coated glow plugs was 2.44%.

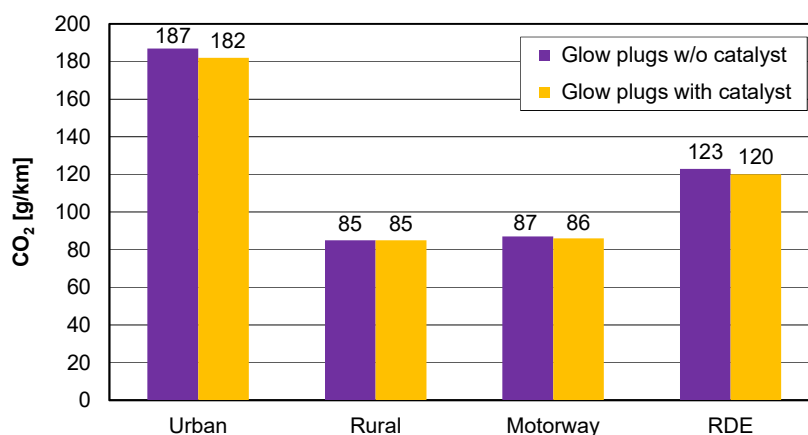


Figure 9. Carbon dioxide road emission in individual test stages and the whole test of a vehicle with a Diesel engine with standard glow plugs and with catalyst coated glow plugs.

The road emission of the number of particulates has a similar character to changes in road emissions of carbon monoxide and hydrocarbons depending on the considered stage of the vehicle's driving route (Fig. 10). In all parts of the road test, this indicator was reduced. The highest values of road particulate emissions were recorded in the case of urban vehicle driving – $1.32 \cdot 10^{13}$ 1/km (for standard glow plugs) and $1.28 \cdot 10^{13}$ 1/km (for catalytic-coated glow plugs) were obtained, as part of for urban driving – $3.71 \cdot 10^{12}$ 1/km (for standard glow plugs) and $3.53 \cdot 10^{12}$ 1/km (for catalytic-coated glow plugs), and for motorway section driving $4.37 \cdot 10^{12}$ 1/km (for standard glow plugs) and $4.11 \cdot 10^{12}$ 1/km (for catalytically

coated glow plugs). The average particle number road emission in the whole test was equal to $7.16 \cdot 10^{12}$ 1/km for standard glow plugs and $6.80 \cdot 10^{12}$ 1/km for catalytic-coated glow plugs. In the whole test, the average value of the nitrogen oxide road emissions reduction with catalytic coated glow plugs was 5.03%.

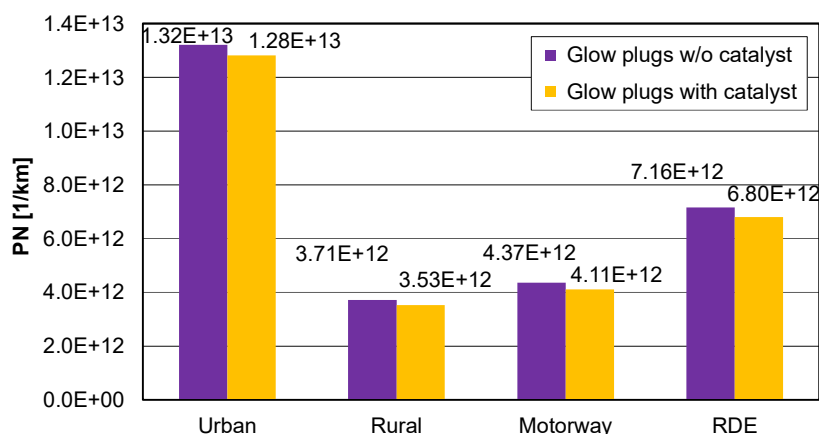


Figure 10. Road emission of the particle number in individual stages of the test and the entire test of a vehicle with a Diesel engine with standard glow plugs and catalyst coated glow plugs.

6. Conclusions

The qualitative and quantitative analysis of exhaust emissions confirmed the catalytic processes efficiency in reducing the emission of harmful exhaust components. Conducted research in real driving conditions confirmed the validity of expanding the existing static tests, and at the same time the results obtained are consistent with the results of tests during engine start-up (given in other publications of the authors (such as in [27, 28])).

In in-cylinder catalyst tests, in real operating conditions, the use of catalytically coated glow plugs resulted in the following average changes relative to standard glow plugs:

- 4% lower mass of carbon monoxide,
- 7% lower mass of hydrocarbons,
- 9% higher mass of nitrogen oxides,
- 6% lower number of solid particles,
- 2% lower mass of carbon dioxide (indicating lower fuel consumption).

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