A Test Method for Individual Control of the Engine’s Ecological Parameters

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Abstract. An analysis of the state-of-the-art has shown that the dominating number of failures falls at internal combustion engines (ICEs): the ignition system - 15-25%, the power system - 30-44%, the exhaust system - 10-15%. It follows from the analysis of modern ICE configurations that the most applicable ICE control method is a selective control method with a subsequent individual adjustment for the current technical condition. The combination of a gas analyzer installed individually in each collector, a motor tester and a test mode former with the function of ensuring test modes allows us to identify failures of the three systems with a high accuracy and to assign an individual corrective action to ensure the specified ecological and economic parameters. A small percentage of throttle opening reliably reflects the information on the mechanical and electrical parts of the injector, matching of the mixture formation and the combustion process at minimal toxicity. In case of a large percentage of throttle opening, the data on the injector section, operation of the ignition system on a rich mixture and significant outlet resistance is informatively reflected.

1. Introduction
The development of the latest engine system designs provides for long-term studies of immense complexity [1, 2, 3, 4]. We cannot carry out comprehensive studies without the use of effective diagnostic methods and means [5, 6, 7, 8]. Despite a large variety of diagnostic tools, the possibility of a full coverage of all ICE systems by the monitoring process remains an open question [9 -11]. The use of test diagnostic methods opens wide opportunities for improving the efficiency of the diagnostic process [12, 13, 14, 15]. They include our method for individual control of exhaust gas toxicity parameters with a full and partial disabling of cylinders with artificial fault simulation [5, 6, 16 - 19].

Purpose of the research. To improve the accuracy of ICE diagnostics by an individual monitoring the exhaust gas toxicity parameters at a full and partial disabling of cylinders with artificial fault simulation.

2. Theoretical research
Comprehensive studies dealing with technical failures of the exhaust system have shown that in 95 % of cases the resistance in the exhaust gas tract varies on the catalytic converter [9, 18, 20]. Let us write a model that takes into account changes in the resistance on individual elements of the catalytic converter to be able to simulate its technical condition [12]:
\[ \Delta p_8 = \sum_{i=1}^{n-8} \Delta p_i = \zeta_1 \frac{l_p}{d_p} \cdot \rho \mathcal{G}^2 \frac{2}{2} + \zeta_2 \frac{g^2}{2} \rho + \]

\[ + \frac{128 \rho Q}{\pi D_f} \left[ \frac{H_2 \left(1-0.5 \frac{H_2}{H-\Delta H}\right) + H_3 \left(1-0.5 \frac{H_3}{H-\Delta H}\right)}{\left(D_j^2 - (d_i^o)^2\right)n} \right] + 0.75 \frac{\rho Q^2}{d_i^4} + \]

\[ + \zeta_5 \frac{\rho \cdot Q^2}{2 \mu \cdot l \cdot b^2 \cdot n} + \frac{\rho \cdot v \cdot Q}{2 n_f \cdot \pi \cdot h_i \cdot K} \cdot \ln \left( \frac{d_o}{d_i} \right) + \frac{12 \cdot v \cdot \rho \cdot L_i \cdot Q}{12 \pi \left(d_i^o - d_i^1\right) \cdot S \cdot d} + 0.055 \left( \frac{\Delta_r}{d_p} + \frac{68}{Re} \right)^{0.25} \cdot \frac{\rho \mathcal{G}^2 l_p}{d_p} \]

where \( \zeta_1, \zeta_2, \zeta_5 \) is the coefficient of friction losses of the exhaust gases against the walls of the inlet branch pipe of the first, second and fifth catalyst sections; \( \mathcal{G} \) is the speed of the exhaust gas flow in the inlet branch pipe, m/s; \( \rho \) is the exhaust gas density, kg/m\(^3\); \( l_p \) is the length and diameter at the inlet and outlet of the catalyst branch pipes, m; \( v \) is the speed of the exhaust gas flow in the next sections, m/s; \( Q \) is the exhaust gas flow through the catalyst, m\(^3\)/s; \( D_f \) is the diameter of the inner catalytic part of the catalyst; \( H_2 \) is the length of the second catalyst section (mechanical stage), m; \( H_3 \) is the length of the third catalyst section (oxidation stage), m; \( \Delta H \) is the length of the gap between the second and third catalyst sections (mechanical and oxidative stages), m; \( d_i^o \) is the outer diameter of the third catalyst compartment, m; \( d_i \) is the inner diameter of the screen exit window, m; \( \mu \) is the flow coefficient; \( l, b \) is the length and width of the window, m; \( n \) is the number of windows, \( n_f \) is the number of filter elements with the height \( h_i \); \( h_i \) is the window length, m; \( d_o, d_i \) is the outer and inner diameter of the filter elements, m; \( K \) is the permeability coefficient of the porous structure, \( L_i \) is the length of the slit corresponding to the length of the second oxidation stage of the filter elements, m; \( d_i^1 \) is the inner diameter of the sixth catalyst compartment, m; \( d_i^1l \) is the outer diameter of the sixth catalyst compartment, m; \( S \) is the width of the annular slit, m; \( \Delta_r \) is the roughness of the inner wall of the branch pipe.

As a result of the generalized model analysis (1), we have established that the most significant components are the pressure drop at the sixth stage. The sixth stage, in its turn, consists of three mechanical sub-stages and two catalytic sub-stages. Let us consider the pressure change at the sixth stage, depending on the resistance coefficient of the three sub-stages (Figure 1).

It can be seen from Figure 1 that the mechanical sub-stage \( \Delta p_6 \) has a more significant impact on \( \Delta p_{61} \) at the maximum possible resistance coefficient the pressure drop is 10 kPa, which is already within the limits set by the manufacturer. The summation of the maximum possible pressure drops at the three sub-stages \( \Delta p_{61}+ \Delta p_{62}+ \Delta p_{63} \) is 20 kPa.
The dependence of the pressure drop $\Delta p_6$ on the resistance coefficient of the catalytic converter sub-stages $K$.

The growing resistance leads to a delay in the exhaust gas volume before the converter, which subsequently leads to a decrease in the neutralization efficiency coefficient.

3. Research methods

For practical implementation, we built an experimental test bench consisting of a VAZ 2110 internal combustion engine with individual exhaust gas sampling points (Figure 2).

![Figure 2. The experimental setup and laboratory measurement tools.](image)

We chose a set of laboratory measurement tools consisting of: MT-10 motor-tester, 4-component INFRACAR M 2.01 gas analyzer, DBD-4 test mode former of the gasoline engine, personal computer.

The input parameters are the change in the electromagnetic injector capacity, the spark gap of the spark plug, and the catalytic converter resistance. The controlled parameters are the ICE temperature, the technical condition of the cylinder-piston group and the gas distribution mechanism, and the oil temperature. The output parameters are the ICE crankshaft speed, CO, CO$_2$, CH, O$_2$. Then, the data was processed in the SigmaPlot software suit, verification and comparative studies were carried out in Excel and Mathcad.

4. The results of experimental research

To confirm the theoretical prerequisites, we carried out experimental research to find the dependence of the exhaust gas composition on the malfunction of the main ICE systems. As a result of processing the experimental data, we obtained graphical dependencies of the exhaust gas composition and the
engine crankshaft speed on the injector capacity, the spark gap of the spark plug, and the catalytic converter resistance (Figures 3, 4, 5, 6, 7).

It can be seen from the obtained graphical dependence (Figure 3) that at the minimum catalytic converter resistance of 10 mm and the nominal injector supply of 100%, the ICE crankshaft speed is minimal. This is due to the accumulation of exhaust gases in the exhaust system and the growing backpressure; at such combination of factors the ICE crankshaft speed amounted to 1870 min\(^{-1}\). This dependence indicates a malfunction of the exhaust system elements.

Based on the experiment results, let us build a dependence of \(O_2\), % on the injector capacity \(F\), % and the catalytic converter resistance \(R\), mm (Figure 4).

It follows from the analysis of the presented diagram (Figure 4) that at the converter resistance of 22 mm and the injector capacity of 94 %, the \(O_2\) indicator noticeably drops to 2.48 % in the diagram, which indicates low fuel content in the fuel-air mixture and an increased resistance of the exhaust gas tract. At a nominal catalytic converter resistance of 34 mm and a minimum fuel supply of 94 %, we observe an increase in the \(O_2\) content to 2.53 %, which directly indicates a malfunction of the fuel supply system.

Let us build an experimental dependence of \(CO_2\), % of the injector capacity \(F\), % and the catalytic converter resistance \(R\), mm (Figure 5).

It can be seen from Figure 5 that the minimum \(CO_2\) indicators are achieved at the maximum fuel injector supply of 106 % and the catalytic converter capacity of 10 mm; at this correlation of factors the content of \(CO_2\) in the exhaust gas sample was 11.1 %, which indicates an incomplete combustion of the fuel-air mixture and a malfunction of the fuel injector. In the area of the nominal injector operation of 100 % and the catalytic converter resistance of 10 mm, we observe a curvature of the diagram, the percentage of \(CO_2\) is 11.57 % in this area, which indicates an optimal supply of the fuel-air mixture.

Let us build an experimental dependence of \(CO\), % of the injector capacity \(F\), % and the catalytic converter resistance \(R\), mm (Figure 6).
An analysis of Figure 6 shows that at the minimum fuel injector supply of 94% and the maximum catalytic converter resistance, the fuel-air mixture is completely burned; at the combination of these factors, it indicates a malfunction of the fuel injector, as evidenced by the content of CO equal to 0.19%. We observe a consistently low content of CO in the range from 94% to 100% of the fuel injector capacity and from 10 to 34 mm of the exhaust system resistance. An increase in the injector capacity to 106% results in a sharp increase in the content of CO in the exhaust gas sample, which is connected with poor combustion of the fuel-air mixture due to oversaturation of the fuel-air mixture, which leads to the highest content of CO of 3.44%. At the aforesaid combination of factors, the highest CO value indicates a malfunction of the fuel injector.

The experimental dependence of CH, ml n⁻¹ on the injector capacity F, % and catalytic converter resistance R, mm is presented in Figure 7.

It can be seen from the presented dependence (Figure 7) that at the fuel injector capacity of 94% and the catalytic converter resistance of 10 mm, there is the minimum content of CH in the exhaust gas sample of 8 ml n⁻¹, which suggests a complete combustion of the fuel-air mixture and, thus, indicates a malfunction of the fuel injector. With an increase in the injector capacity and a decrease in the catalytic converter resistance, we observe an increase in the content of CH in the exhaust gas sample, which indicates an incomplete combustion of the fuel-air mixture.
5. Conclusions
As a result of the chronometration of the diagnostic process operation, the time spent on determining the technical condition of the injectors, spark plugs and the catalytic converter is 22 man-minutes (when conventional methods are used, it is 105 man-min.). The creation and implementation of the test diagnostic methods and means allows us to obtain annual savings per one diagnostic post within 699,700 – 855,200 rubles.

References
[1] Magaril E, Magaril R and Bamburov V 2014 Combustion, Explosion, and Shock Waves 50(1) 75-79
[2] Czech P and Bakowski H 2013 Transport Problems 8(3) 85–91
[3] Gritsenko A, Zadorozhnaya E and Shepelev V 2018 Tribology in Industry 40(2) 300-310
[4] Gritsenko A, Glemba K and Vozmilov A 2018 13th International Conference on Organization and Traffic Safety Management in Large Cities - SPbOTSIC (Transportation Research Procedia vol 36) ed Zhankaziev S (Saint Petersburg: Russian Federation/Elsevier BV) pp 237-244
[5] Gritsenko A, Kukov S and Glemba K 2016 2nd International Conference on Industrial Engineering-ICIE (Proc. Engin. vol 150) ed Radiono AA (Chelyabinsk: Russian Federation/Elsevier Ltd) pp 1182-87
[6] Plaksin A, Gritsenko A and Glemba K 2016 2nd International Conference on Industrial Engineering-ICIE (Proc. Engin. vol 150) ed Radiono AA (Chelyabinsk: Russian Federation/Elsevier Ltd) pp 1188-91
[7] Becciani M, Romani L, Vichi G, Bianchini A, Asai G, Minamino R, Bellissima A and Ferrara G 2019 Energies 12(8)
[8] Mohammadpour J, Franchek M and Grigoriadis K 2012 International Journal of Engine Research 13(1) 41-64
[9] Kyratatos N, Tzanos E and Papadopoulos C 2003 International Journal of Engine Research 4(3) 219-31
[10] Vichi G, Stiaccini I, Ferrari L, Ferrara G, Bellissima A and Minamino R 2014 SAE International Journal of Engines 8(1) 288-302
[11] Bi X, Cao S and Zhang D 2019 IEEE Access 7(8651509) 27756-68
[12] Delvecchio S, Bonfiglio P and Pompoli F 2018 Mechanical Systems and Signal Processing 99 661-683
[13] Jardine AKS, Lin D and Banjevic D 2006 Mechanical Systems and Signal Processing 20(7) 1483-1510
[14] Yulinheth Cardenas E, Guillermo Valencia O and Eras JC 2018 Journal of Engineering Science and Technology Review 11(3) 163-167
[15] Mechri W, Vu H-C, Do P, Klingelschmidt T, Peysson F and Theilliol D 2018 Advances in Intelligent Systems and Computing 635 380-389
[16] Orczyk M and Tomaszewski F 2017 7th International Congress on Combustion Engines - ICCE (MATEC Web of Conferences vol 118) ed Jacek P (Poznan: Poland/EDP Sciences)
[17] Boldin AP, Sarbaev VI and Aksenov PV 2017 International Journal of Mechanical Engineering and Technology 8(12) 933-943
[18] Zielińska E, Girtler J and Lejda K 2017 Polish Maritime Research 24(1) 81-87
[19] Permyakov VV, Rudnev VS, Usoltsev AA, Kaminskiy NS and Zorin AV 2015 International Journal of Applied Engineering Research 10(16) 37426-27
[20] Gorbunova A, Anisimov I, Fadyushin A, Tishin M and Zakharov D 2019 All-Russian Research-to-Practice Conference on Ecology and Safety in the Technosphere: Current Problems and Solutions (IOP Conference Series: Earth and Environmental Science vol 224) (Yurga: Russian Federation/Institute of Physics Publishing)