Information and analytical system to monitor operating processes and environmental performance of vehicle propulsion systems

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Abstract. The article describes the peculiarities of using the information and analytical system to study the operating processes of vehicle propulsion systems and to assess their environmental performance, particularly fuel consumption and harmful emissions under operating conditions. The study provides the functional structure of the information and analytical system. It contains the subsystems that enable to obtain and analyze data about the operating process in the cylinder, the subsystem for obtaining data from the engine control system, the subsystem for obtaining data about the operating mode of the propulsion system, the subsystem of data analysis and forecasting the vehicle propulsion system indicators in different operating modes. The case of using the information and analytical system has been shown to study the influence of exhaust gas recirculation on fuel efficiency and environmental performance indicators of the vehicle propulsion system in separate modes and under operating conditions.

1. Introduction
A propulsion system (PS) is the main source of energy for the vehicle motion, it is a fuel consumer and environmental pollutant. The predominant type of PSs, common in vehicles nowadays, is the one based on various types of internal combustion engines (ICE). Power, fuel consumption, emissions, as well as weight, dimensions and cost of different PSs with one type of engine essentially depend on the design features of fuel and air supply systems and exhaust gas cleaning systems. But the level of environmental performance of the propulsion systems characterized by the efficiency of fuel consumption and the level of environmental pollution is largely determined by the arrangement and the nature of the engine operating processes. Therefore, improving the efficiency of fuel consumption and reducing harmful emissions of vehicle propulsion systems are always associated with the study of engine operating processes.
The development of calculation methods to analyze the operating processes of internal combustion engines, the generation of pollutants during combustion, and the influence of heat transfer processes on engine effective performance are highlighted in numerous experimental and theoretical studies of many scientists [1–6].

The [7–11] describe the equipment for obtaining, analyzing and processing the results of experimental studies of ICE operating process.

The overall structure of monitoring the parameters of vehicle propulsion systems is presented in a previously published paper [12]. The work of authors [13–19] presents the algorithm for modeling the main processes of vehicle propulsion system. It takes into account the operating conditions and the cases of using a mathematical model "engine - catalytic converter". It enables to assess the efficiency of applying rapid heating systems based on thermal accumulators.

However, to effectively monitor the parameters of vehicle propulsion systems, to analyze their environmental performance in specific operating modes, it is relevant to automate information obtaining and processing. Based on the analysis of the obtained data, it is necessary to evaluate vehicle performance in standardized driving cycles, the efficiency of ways for improving fuel economy and environmental performance of vehicles under operating conditions.

2. The functional structure of monitoring vehicle propulsion systems

To do this, the information and analytical system for monitoring the parameters of vehicle propulsion systems and their environmental performance has been developed. Its functional structure is presented in figure 1.

The main elements of the system are: a subsystem for obtaining data from the strain gauge in the engine cylinder (A, B levels), a subsystem for obtaining data about the operating mode of the propulsion system (C level), a subsystem for obtaining data from the engine control system (D level), a subsystem of data analysis about the parameters of the working body in the cylinder (E, F levels), a subsystem of data analysis and forecasting the vehicle propulsion system parameters in different operating modes (G, H levels).

The system operates as follows. At the input of the process of A level, a working body comes to the pressure sensor in the ICE cylinder. It consists of fuel $G_{\text{FUEL}}$, air $G_{\text{AIR}}$ and / or combustion products (exhaust gas) $G_{\text{EG}}$. It is characterized by pressure $p$, temperature $T$, volume $V$, and mass $m$. In the process of A level, the pressure $p$ of the working body in the cylinder is converted into an electrical voltage $U_p$ by a sensitive element of the pressure sensor. The received electrical voltage $U_p$ is converted into information data and is stored in the memory of the information device (ID) by an analog-to-digital converter. When converting the pressure, a part of thermal energy $Q_{PS}$ coming to the sensitive element of the pressure sensor is released into the environment. It is characterized by pressure $p_0$ and temperature $T_0$. At the output of the process of A level, electrical signals from the ignition moment $U_0$ and the crankshaft rotation speed $U_n$ are added to the digital data on the electrical pressure signal in the cylinder $U_p$. They are measured on certain engine control system (ECS) sensors. The information on the electrical pressure signals, the ignition moment and the crankshaft rotation speed is recorded in the ID. To ensure the optimum temperature condition of the sensitive element of the pressure sensor and the stable characteristics of the pressure conversion into the electrical voltage at the B level, the temperature of the sensitive element $T_{PS}$ is controlled by circulating the coolant $G_{\text{COOL}}$ in the sensor cooling chamber.

The input of the process of C level is the mechanical energy of the engine crankshaft rotation. It is characterized by the torque $M_c$ and the crankshaft rotation speed $n$. When measuring the torque $M_c$ and the crankshaft rotation speed $n$, they are converted into electrical signals and information data characterizing the engine operating mode. The measurement is carried out using torque and rotation speed sensors mounted on the shaft of the engine energy consumer. The received information is recorded in the ID memory and comes to the ECS. The data on the engine operating mode is necessary to establish the relationship between the parameters of the operating process in the engine cylinder and its effective performance.

The input of D level is provided by a diagnostic interface of the OBD standard which receives the operating data from the ECS. The D level process decodes the OBD data for obtaining the engine control parameters by a special adapter and software. The obtained data are recorded in the ID.
memory. The engine control parameters are needed to identify the engine operating conditions influencing the nature of its operating process.

Figure 1. Functional structure of the information and analytical system for monitoring the parameters of vehicle propulsion systems.

The output data of A, C and D levels about the cylinder pressure, engine operating mode and engine control parameters are the input data for E level. It enables to determine the data about the state
parameters of the working body in the cylinder and to analyze the efficiency of the engine operating cycle. As a result, the following data are received and recorded in the ID memory: data about pressure $p$, temperature $T$, volume $V$ and mass $m$ of the working body in the cylinder, the combustion function $x(\phi)$, indicated parameters, in particular, the indicated mean pressure $p_i$, the indicated efficiency $\eta_i$, indicated specific fuel consumption $g_i$ and mechanical loss components, in particular, the mean pressure of mechanical loss $p_m$, the mean pressure of pump loss $p_g$, the power of mechanical loss $N_m$, the power of pump loss $N_g$ of the engine.

At F level, the obtained data are generalized to determine the influence of the operating mode and the engine control parameters on the nature of the engine operating process. Based on these data the mathematical model of the propulsion system operating process is specified.

The next G level involves modeling and forecasting fuel economy, energy and environmental performance of the propulsion system in different operating modes and operating conditions. For this purpose, the mathematical model of the "engine - catalytic converter" system [13, 15] is used. The mathematical model is based on the method of the volume balance [5]. It enables to determine the fuel economy, energy and environmental parameters of the PS in accordance with the design parameters of the engine, fuel and air supply systems and the exhaust gas (EG) cleaning system, operating mode and control parameters, fuel type and environment parameters. At the output of the G level process, modeling results in propulsion system efficiency indicators, in particular, effective power $N_e$, fuel consumption $G_{\text{FUEL}}$, carbon monoxide emissions $G_{\text{CO}}$, hydrocarbons emissions $G_{\text{CmHn}}$, nitrogen oxides emissions $G_{\text{NOx}}$, carbon dioxide emissions $G_{\text{CO2}}$ in different engine operating modes and the patterns of their variation under operating conditions are obtained.

To improve the efficiency of the vehicle propulsion system at H level, its operating modes, control parameters and technical condition are controlled. It provides the necessary influence on the input data of A and C levels.

3. The peculiarities of using the system for monitoring the vehicle propulsion systems

The developed information and analytical system for monitoring the parameters of vehicle propulsion systems has been used when analysing the effect of exhaust gas recirculation (EGR) on the indicated, effective and environmental parameters of the propulsion system with the gasoline engine.

3.1. The object of the study

The object of experimental research was a four-stroke, spark ignition, liquid cooling, electronic controlling gasoline engine VW BBY equipped with EG cleaning and recirculation systems (figure 2). During the research, the engine was installed on the SAK-670 brake test bench with a GPF a17h electric braking device with a power of 250 kW and a maximum rotational speed of 3200 min$^{-1}$. The main technical parameters of the VW BBY engine are given in table 1.

![Figure 2. The object of the study – VW BBY engine.](image-url)
Table 1. The main technical parameters of the VW BBY engine.

| Title                                           | Specification                                                                 |
|-------------------------------------------------|-------------------------------------------------------------------------------|
| Fuel type                                       | A-95 gasoline                                                                |
| Number / arrangement of engine cylinders        | 4 / inline                                                                    |
| Engine displacement, l                          | 1.39                                                                          |
| Diameter of cylinder / piston stroke, mm        | 76.5 / 75.6                                                                   |
| Compression ratio                               | 10.5                                                                          |
| Engine power, kW / crankshaft rotation speed, min\(^{-1}\) | 55 / 5000                                                                     |
| Torque, N·m / crankshaft rotation speed, min\(^{-1}\) | 126 / 3800                                                                   |
| Engine control system                           | Magneti Marelli 4MV with sequential multipoint fuel injection, individual ignition coils and knock control |
| Exhaust gas cleaning system                     | Two-stage (two three-component catalytic converters) with rapid heating and exhaust gas recirculation |

3.2. Obtaining data about the parameters of the engine operating process

Main measuring elements of the information and analytical system were mounted at the investigated engine to obtain data about the operating cycle parameters for implementing the processes at A and B levels. Figure 3 shows a scheme of strain gauge mounting within a cylinder head of VW BBY engine. The main technical parameters of the pressure sensor are shown in table 2. Figure 4 shows the pressure sensor, analog-to-digital converter to record electric signals of pressure, crankshaft rotation speed, ignition moment and the example of data display at the ID. The stored data are exposed to further processing by a specialized software to obtain the engine operating cycle characteristics in different operating modes.

![Figure 3](image-url)  
Figure 3. The pressure sensor mounting within a cylinder head of VW BBY engine: 1 – cylinder block, 2 – cylinder head, 3 – piston, 4 – combustion chamber, 5 – spark plug, 6 – cooling chamber of the engine, 7 – measuring pipe, 8 – fitting to connect the sensor and the measuring pipe, 9 – cooling chamber of the sensor, 10 – pressure sensor, 11 – contact membrane, 12 – measuring membrane, 13 – sensitive element.
Table 2. Basic technical parameters of the pressure sensor.

| Title                               | Specification                                                                 |
|-------------------------------------|------------------------------------------------------------------------------|
| Converter type                      | strain gauge                                                                 |
| Implementation                      | distributed scheme: the open contact membrane is connected by a rigid stem with the measuring membrane |
| Membrane material                   | high-strength titanium alloy                                                 |
| Sensitive element                   | silicon strain resistors connected according to a full bridge scheme         |
| Pressure measuring range, MPa       | 0…10                                                                         |
| Maximum temperature of the          |                                                                               |
| sensitive element, °C               | 350                                                                          |

Figure 4. The pressure sensor (a), analog-to-digital converter (b) to record electric signals of pressure, crankshaft rotation speed, ignition moment and the example of data display at the information device (c).
3.3. Obtaining data about the operating mode and control parameters of the propulsion system

A standard measuring system of the brake test bench provides the implementation of C level process. It displays the information about the torque $M_e$ and the rotation speed $n$ of the braking device shaft on the ID screen. The ID provides obtaining and decoding of the diagnostic data from the ECS using a special OBD standard adapter and a software during D level process. The obtained information about the torque $M_e$, the rotation speed $n$ and the ECS parameters is stored in the ID memory to be used in further analysis. Figure 5a shows a general view of the ID with a connected adapter and OBD software. A file fragment with the data about the propulsion system operating mode and the ECS parameters is also shown in figure 5b.

![Information device with a connected adapter and OBD software](image)

**Figure 5.** Information device with a connected adapter and OBD software (a) and a file fragment with the data about the propulsion system operating mode and the engine control system parameters (b).
3.4. Analyzing the operating process efficiency of the propulsion system with exhaust gas recirculation
As a result, the indicated diagrams of the VW BBY operating cycle when using the EGR and without it were obtained at the process output of E level. Indicated diagrams in different operating modes of the engine and with different EGR degrees $R_{EG}$ were generalized using a feedback at F level. For example, figures 6, 7 show indicated diagrams of the operating cycle and the dependencies of the engine parameters from $R_{EG}$ in operating mode with the crankshaft rotation speed $n = 2400 \text{ min}^{-1}$ and a throttle position $\phi_{tr} = 14.55 \%$. The diagrams show that the pressure $p$ on compression and expansion lines (for crankshaft rotation angles $\varphi = 180...540 \text{ deg}$) is increased when using the EGR, but a maximum pressure is decreased by 7%. Moreover, the pressure $p$ on intake line is increased because of fresh charge temperature increase and the pressure $p$ on exhaust line is decreased because a part of exhaust gas goes to intake manifold. Due to this, gas work of the cycle when using the EGR almost did not change and power loss in gas-exchange processes is reduced. The analysis of the obtained indicated and effective engine performance depending on the EGR degree (figure 7) enabled to find optimum $R_{EG}$. It provided minimum value of effective specific fuel consumption $g_e$. The dependencies of VW BBY characteristics from $R_{EG}$ in this engine operating mode were also received.

![Figure 6. Indicated diagrams of the VW BBY operating cycle.](image)

As dependencies show (figure 7), maximum in-cylinder pressure $p_z$ and temperature $T_z$, and average speed of pressure increase during burning $\Delta p/\Delta \phi$ are reduced when increasing $R_{EG}$. However, $p_z$, $T_z$, $\Delta p/\Delta \phi$ intensity of reducing to $R_{EG} = 18 \%$ is about 3...3.5 times less than after $R_{EG} = 18 \%$. Such dependency is explained by the fact that ignition timing angle $\theta$ increases to $R_{EG} = 18 \%$ and decreases after $R_{EG} = 18 \%$.

The power of the pump loss $N_p$ and the power of total mechanical loss $N_m$ are reduced when increasing $R_{EG}$. Indicated power $N_i$ almost does not change to $R_{EG} = 18 \%$ because of $\theta$ optimization. Burning deteriorates significantly when further increasing $R_{EG}$ and $\theta$ optimization does not give effect.

Effective power $N_e$ of the engine is increased somewhat by $R_{EG} = 3...5 \%$ and stays at power level as for engine operation without the EGR by $R_{EG} = 5...17 \%$ because of $N_m$ reduction and $\theta$ optimization. Minimum effective specific fuel consumption $g_e$ is achieved at $R_{EG} = 13...17 \%$. Effective specific fuel consumption $g_e$ is reduced by 8.7% comparatively with the engine operation without the EGR. Maximum effective power is achieved at $R_{EG} \approx 5 \%$. Optimum $R_{EG}$ in the given operating mode of the engine is 17% in terms of fuel economy improvement.

3.5. Forecasting the environmental performance of the propulsion system under operating conditions
When implementing the G level process, fuel consumption and emissions of the vehicle propulsion system in the driving cycle according to UNECE Regulation No. 83-04 were determined using the mathematical model of the "engine – catalytic converter" system. Optimum EGR degree characteristics were obtained to improve environmental performance of the VW BBY engine using the feedback of H level. The influence of the EGR on fuel consumption and emissions of the vehicle
propulsion system in the driving cycle was analyzed using these characteristics. For example, figure 8 shows fuel consumption and emissions in the investigated driving cycle modes. It shows that fuel consumption per cycle is reduced by 3.6 %, carbon monoxide emission per cycle is reduced by 3.34 %, and hydrocarbons emission per cycle is reduced by 4.4 %, nitrogen oxides emission per cycle is reduced by 11.3 % when using the EGR.

**Figure 7.** The dependencies of the engine characteristics from $R_{EG}$.  

**Figure 8.** Fuel consumption and emissions of the vehicle propulsion system in the driving cycle modes.

Thus, using the developed information and analytical monitoring system of the vehicle propulsion system parameters enables to analyze and optimize the propulsion system control parameters to improve its environmental performance.

### 4. Conclusions

Automation of information obtaining and data processing using modern information technologies is actual for effective monitoring of the vehicle propulsion system parameters and their environmental performance in certain operating modes. The analysis of the obtained data enables to evaluate the efficiency of ways for improving vehicle fuel economy and environmental performance under operating conditions.

The developed information and analytical monitoring system of the vehicle propulsion system parameters provides obtaining the data about the propulsion system operating process, control parameters and operating mode. It enables to analyze the operating process efficiency and to forecast the propulsion system environmental performance with feedbacks. They help optimize the operating modes, control parameters and technical condition of the propulsion system under operating conditions.

The information and analytical monitoring system of the vehicle propulsion system parameters has been used to analyze exhaust gas recirculation influence on indicated, effective and environmental performance of the propulsion system equipped with VW BBY gasoline engine. As research results have found that controlling the exhaust gas recirculation optimization enables to improve the vehicle
propulsion system environmental performance. It implies, in particular, reducing fuel consumption by 3.6 %, carbon monoxide emission by 3.34 %, hydrocarbons emission by 4.4 %, nitrogen oxides emission by 11.3 % in the driving cycle modes according to UNECE Regulation No. 83-04.

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