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The Performance of a Car with Various Engine Power Systems – Part I

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Abstract: The automotive sector has recently undergone enormous transformations, mainly dictated by the requirements to reduce the negative impact of the automotive industry on the natural environment. Reducing emissions from this sector has become the main driver of change in modern motor vehicles. Unfortunately, due to economic differences in the world, this process is not the same in all countries. Despite these differences, however, even in less developed countries, efforts are made to reduce vehicle exhaust emissions. The work conducted road tests, bench, calculated comparative studies of fuel, economic, environmental and energy performance of a serial car with a standard carburetor power system and equipped with an electronic gasoline injection system and a three-component catalytic converter under operating conditions.

Keywords: Gasoline engine, injection system, fuel economy, European urban ride cycle

1. Introduction and Literature Review

The road transport sector has recently undergone enormous changes related to the development of internal combustion engines (including mainly those aimed at reducing the emission of toxic compounds) [1], fuels and operating fluids used [2], construction materials for the construction of vehicles [3], infrastructure development and changes in vehicle drive systems [4]. Currently, for many years there has been a discussion on improving the environmental properties of motor vehicles [5–7], taking into account technical, legal and operational factors [8]. Currently used

reciprocating combustion engines must be able to generate the least harmful effects to the environment [9,10], which means that they must generate low emission of exhaust fumes and noise [11]. The noise generated by internal combustion engines was discussed in the following works [12,13]. Moreover, the internal combustion engine must ensure reliable operation for a very long time under variable load conditions [14-16].

Every machine powered by an internal combustion engine has an effect on the general level of anthropogenic pollution [17]. Global climate changes caused by heating of lower layers of atmosphere, the surface of Earth and surface water result from intensification of the greenhouse effect [18]. One of the reasons for global warming is exhaust emissions from means of transport. Many scientific papers have been devoted to the issues of exhaust emissions from internal combustion engines, for example [19-26].

In operating conditions, cars with outdated fuel supply systems for spark ignition engines continue to operate. Moreover, these are mainly cars with carburetor engines with a service life of more than 10 years, which currently do not comply with any European environmental standards [27,28]. According to expert estimates [28], the passenger car fleet of Ukraine at the end of 2019 had such an indicative structure for environmental properties:

- corresponding Euro-0 - 4470-4870 thousand units. (66-72%),
- corresponding Euro-1 - 60-130 thousand units (1-2%),
- corresponding Euro-2 - 1220-1350 thousand units (18-20%).

The vast majority of Euro-0 and Euro-1 cars are in operation with carburetor power systems and do not meet current environmental standards. Carrying out its mission, road transport, as a rule, causes a negative impact on the environment, emitting a large amount of pollutants into the atmosphere. The main factors that worsen the environmental situation in Ukraine are: aging of the car fleet; mass import of environmentally hazardous cars of an obsolete design, were in operation in other countries (environmental level of the 90s of the last century); lack of government regulation aimed at the economic promotion of the introduction of equipment and technologies that provide enhanced indicators of environmental safety and energy conservation, for example, aimed at reduction of specific emissions of vehicles per unit of transport work or mileage; lack of effective control over the technical condition of vehicles in operation [29].

Therefore, improving environmental performance, along with the energy and fuel efficiency of cars with outdated power systems in operating conditions, can be achieved through the use of special measures. The most effective is to replace the carburetor system with a modern gasoline injection system with a toxicity reduction system of the three main harmful components: carbon monoxide CO, hydrocarbons C_mH_n, nitrogen oxides NOx. Neutralization systems consist of devices that provide more than 90% effective cleaning of engine exhaust gases from toxic components [30].

The effectiveness of a three-component catalytic converter depends on the composition of the fuel-air mixture. Due to this, such systems of fuel supply best contribute to the processes that provide the required composition of the mixture in all operating modes of the car [32,32]. For this causes, in this study, it was proposed to change the fuel supply system of a spark-ignition engine operated in large numbers of older vehicles in Ukraine.

2. Data and Methods

For carrying out comparative studies of the modern injection system, the widespread VAZ-21051 passenger car with a carburetor engine, model 2101, was chosen. The LH-Motronic adaptive electronic injection system was chosen as the injection system. It includes: an electronic (static) ignition system, a microcomputer control of the ignition timing, an electronic knock control system (knock sensor), a neutralization system with feedback, a gas vapor recovery system (EVAP - Evaporative Emission Control System) [31]. As a device for reducing exhaust toxicity, a modern three-component catalytic converter is used. Bench research of an engine with various power systems allows you to determine all the advantages and performance only at steady-state conditions at fixed speeds of the crankshaft. Such studies cannot fully take into account the influence of operational factors on fuel efficiency and environmental performance of a car [33]. The impact of operating conditions on performance and environmental standards for vehicles with a gross weight of up to 3.5 tons is checked according to the European driving cycle modes on a roller stand in accordance with UNECE Regulation No. 83 [34].

There is another approach that allows, with a slight error, to determine the performance of the car in the driving cycle using a mathematical model. Modeling the movement of the car in the driving cycle allows you to determine its operational performance in the system "driver-car-road." Mathematical models are refined to take into account the influence of various factors on fuel efficiency and environmental performance of cars in operating conditions [35].

The refinement of the mathematical model is that for a feedback injection system, a condition is fulfilled in which the coefficient of excess air is stoichiometric in all driving modes of the vehicle along the driving cycle. In the model with a carburetor system, the accelerator pump operation and the time of its impact on the engine performance during acceleration were taken into account. The movement of the car along the driving cycle is described by a system of differential and algebraic equations that establish the dependence of the change in engine torque Mk on the conditional speed of the car or its acceleration or deceleration, taking into account the loss of a certain amount of torque to overcome the rolling resistance forces, as well as the inertia forces of moving masses.

The torque during the acceleration of the car with a locked clutch is determined by the equation: sequentially (see Eq. 1).

$$M_k = \left[I_A + \frac{1}{\eta_\tau} \cdot I_{np}\right] \frac{d\omega_A}{dt} + M_{rm}\,, \quad (1)$$

where: I_A is moment of inertia of the engine [kg·m^2]; η_τ is transmission efficiency; I_{np} is reduced moment of inertia of the moving masses of the vehicle [kg·m^2]; $\frac{d\omega_A}{dt}$ is angular acceleration (deceleration) of the crankshaft of the engine [s^{-2}]; M_{rm} is moment of resistance of movement of the car [Nm].

In load modes engine performance is defined as a function of two independent variables: engine crankshaft speed (nd) and engine load (Mk). To account for fuel consumption from torque change and engine shaft speed, it can be described as a second-order polynomial (Eq. 2):

$$Gпал(nd, M_к) = A_0 + A_1 \cdot nd + A_2 \cdot M_к + A_3 \cdot nd^2 + A_4 \cdot {M_к}^2 + A_5 \cdot nd \cdot M_к \quad (2)$$

where: $A_0 \ldots A_5$ – constant coefficients of polynomial approximation; *nd* - engine speed [rpm].

To determine the influence of the type of power supply system on fuel efficiency, energy and environmental performance of a gasoline engine and a vehicle in operation with outdated power supply systems, it is necessary to solve the following tasks:

1. Conducting bench tests of an engine with a standard power supply system and a gasoline injection system with feedback and a device for reducing exhaust toxicity;
2. Implementation of the European driving cycle on a simulating roller stand of a car with a new injection system with feedback, gas vapor recovery and neutralization systems;
3. Car road tests using a standard power system and gasoline injection system.

2.1 Test Bench

During bench tests, a three-component catalytic converter was installed in the exhaust system of the engine. Previously, in two-component (oxidative) converters, platinum and palladium, which provide oxidation of CO to CO_2, and C_mH_n in CO_2 and H_2O, were used as catalysts, but the three-component catalytic converter contains rhodium, which ensures the reduction of NO_x into molecular nitrogen N_2. The reaction and results of oxidation of the exhaust gases in a three-component catalytic converter was presented in Table 1.

Table 1 reaction and results of oxidation of the exhaust gases in a three-component catalytic converter. Source: authors

Exhaust gas intel	Exhaust gas output
NO_x	N_2
CO	CO_2
C_mH_n	H_2O
Reaction	
$NO_x – H_2 = N_2 + H_2O$	
$CO + O_2 = CO_2$	
$CH + O_2 = CO_2 + H_2O$	
$NO_x + CO = N_2 + CO_2$	

The study of engine performance was carried out in an experimental setup, which consisted of the following elements presented in Fig. 1.

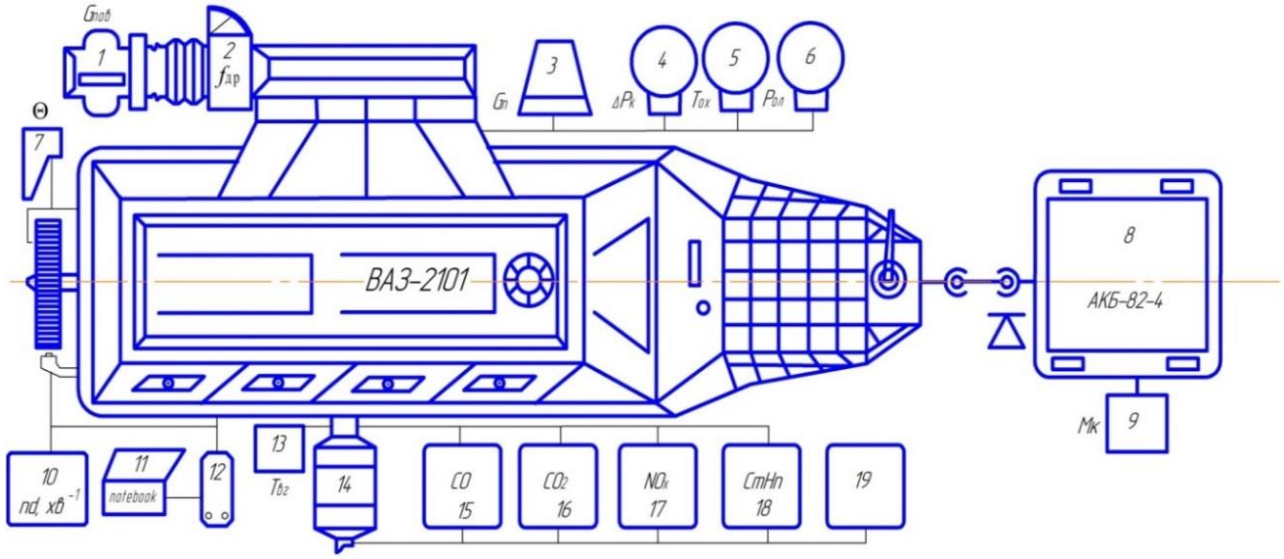


Fig. 1 Scheme of the experimental installation of SSEU-55, description in the text. Source: authors

The symbols shown in Figure 1 mean respectively: 1 – Air flow volume type RG-100-1; 2 – a device for measuring the position of the throttle; 3 – a device for determining the fuel consumption (weight method); 4 – a device for measuring the vacuum in the intake manifold; 5 – a device for measuring the temperature of the engine coolant; 6 – an apparatus for measuring oil pressure in the engine lubrication system; 7 – device for measuring the ignition timing angle; 8 – loading stand; 9 – a device for measuring engine torque; 10 – a device for measuring the rotational speed of the crankshaft of the engine; 11 – personal computer; 12 – a sequential diagnostic device K-Line; 13 – a device for measuring the temperature of the exhaust gas; 14 – three-component catalytic converter; 15, 16, 17, 18 – instruments for measuring concentrations of CO, C_mH_n, NO_x, CO_2; 19 – is a device for determining the pressure in the exhaust system.

To study the engine performance, we used a stationary loading stand SGEU-55 with a three-phase current motor, 55 kW power and a nominal rotor speed of 3000 rpm, which is actuated from the control panel. The torque Mk is determined by an electric dynamometer, its pulses, which were converted from electric to analog, watched the current value of Mk. Fuel consumption was determined by weight. Air flow rate was determined by a rotary WG-100-1 volumetric gas meter. In the case of tests with an exhaust gas analyzer, it is quite important to properly calibrate the measuring apparatus [36]. To measure the NO_x content of the exhaust gas, a 344-CL-14 gas analyzer was used, which implemented a chemiluminescent method. To determine the concentrations of CO, CHH and CO_2 in the exhaust gases of the engine, the gas analyzer META Autotest-01.03 was used. Measuring range for CO – 0 ... 7%; C_mH_n - 0… 3000 mln^{-1}; CO_2 - 0 ... 16%.

3. Results and Discussion

The comparative characteristics of the engine with the standard power supply system and the injection system in high-speed active idle speed were determined (Fig. 2).

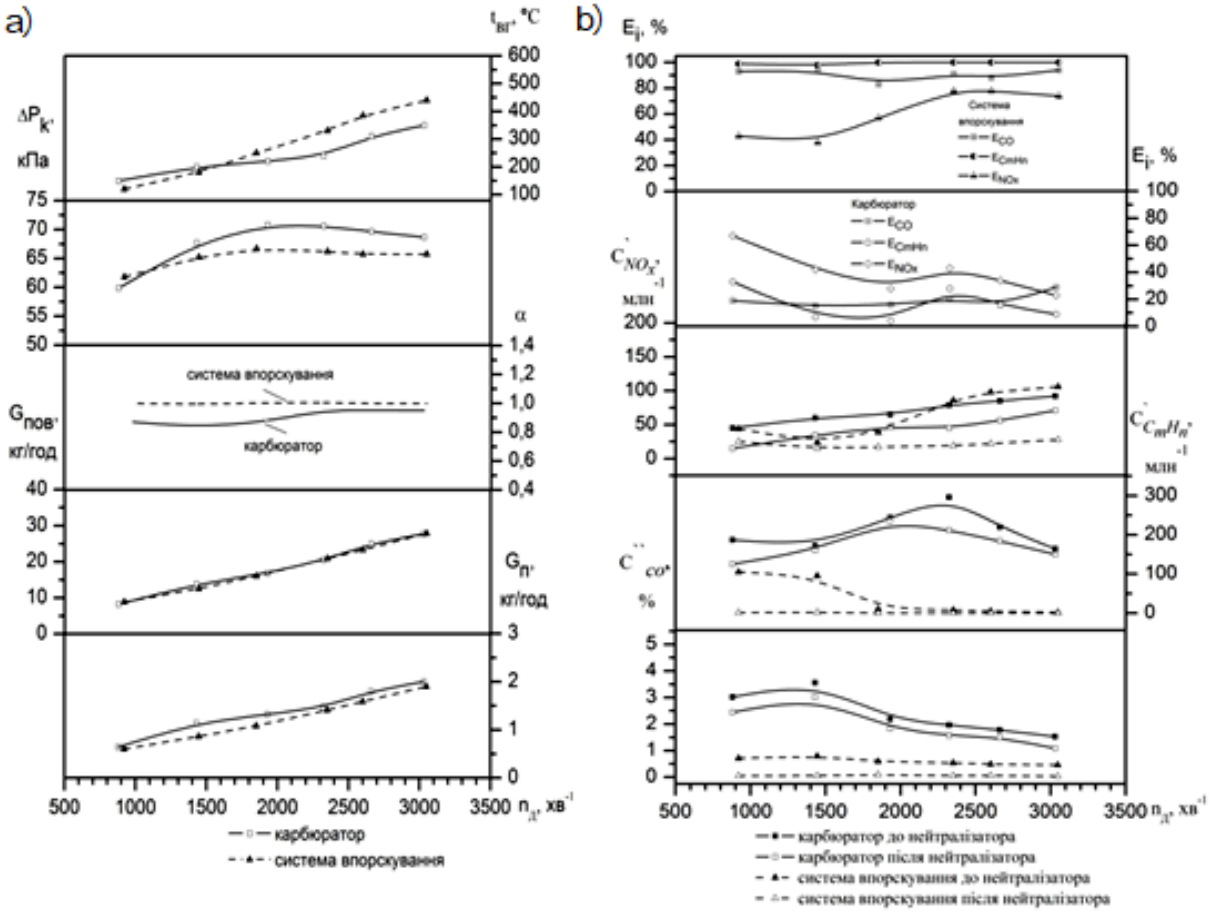


Fig. 2 Characteristics of the active idling of the engine 4F7,6 / 6,6 with different type of power system: a) fuel efficiency indicators, b) environmental performance. Source: authors

As can be seen, the injection system reduces fuel consumption, on average by characteristic, by 11.1% (Fig. 2a). Characteristics with the carburetor system in active idle modes have an enriched composition of the fuel-air mixture, which is characterized by high concentrations of CO, C_mH_n in the exhaust gases during sampling to a three-component catalytic converter compared to these indicators when applying the system. NO_x concentrations in idle modes are negligible and the difference for different power systems is close to the measurement accuracy of this substance.

As can be seen from Fig. 2b, the injection system provides effective neutralization of CO, C_mH_n within 88...100% throughout the speed mode. The efficiency of NOx neutralization at rotation frequencies of 2350…3050 rpm is in the range of 73…78%, and only at low frequencies the efficiency of NO_x neutralization decreases to 43.2%, which is explained by the decrease in the exhaust gas temperature (tvg). Neutralization efficiency with a standard power system for all components is much lower except for the neutralization of NO_x at low speeds, which can be explained by the higher temperature (tgg) before the neutralizer.

In Fig. 3 shows the load characteristics of the engine at a speed of crankshaft of the engine 2000 rpm. As can be seen from Fig. 3a), the injection system improves the fuel economy of the engine. Reduction of specific fuel consumption by load characteristics is on average 5%. The engine's energy performance increased: at full load, the engine power with the injection system increased by 6.6%.

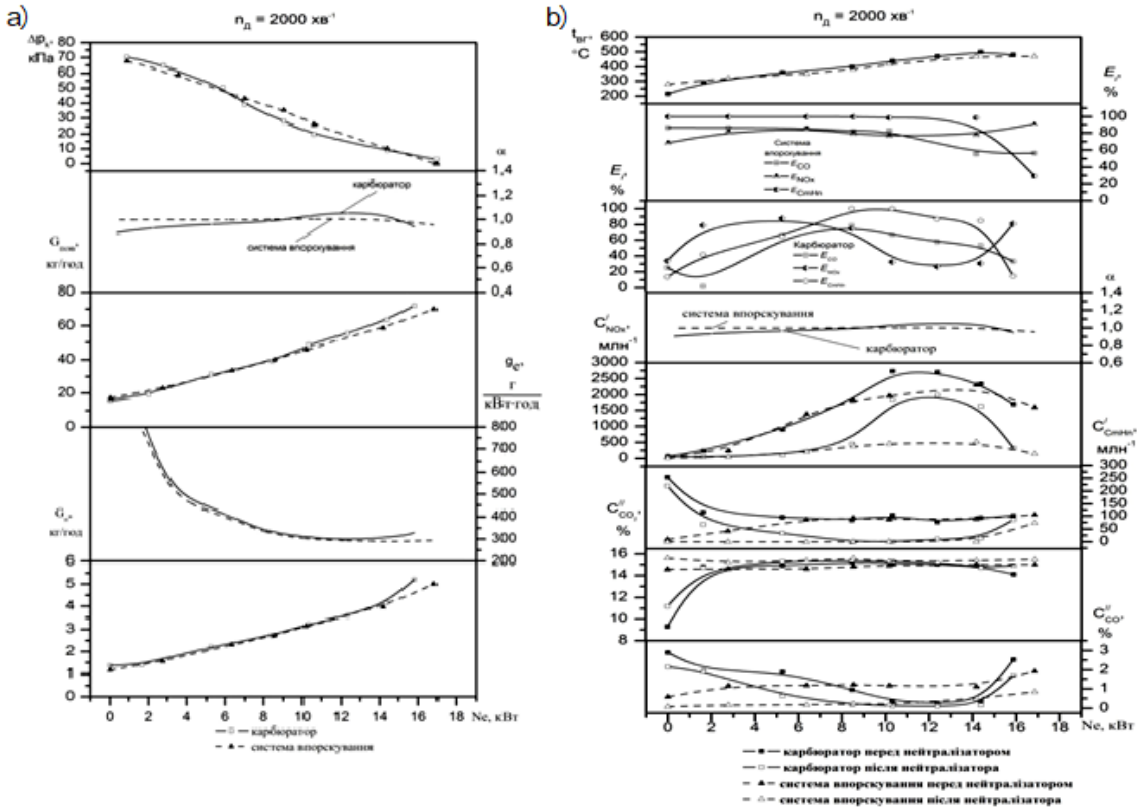


Fig. 3 Load characteristics of the engine 4F7.6 / 6.6 with different type of power system: a) fuel efficiency indicators, b) environmental performance. Source: authors

Environmental performance of the engine is improved with the injection system, as evidenced by the low concentrations of harmful substances in the exhaust gases before and after the three-component catalytic converter (Fig. 3b). The engine with a regular carburetor system in low load and idle modes has higher concentrations of incomplete combustion products (CO, C_mH_n) compared to the injection system (Fig. 3b).

In the range of average loads and close to full under the carburetor system, NOx concentrations are also higher. This is due to the depletion of the composition of the mixture. The flue gas temperature (tgg) is higher at loads where the air-fuel mixture is poorer with one system or another. At the site of the most efficient combustion (α = 1.03…1.05), where the concentrations of CO and C_mH_n are minimal, the concentration of NOx is highest. This is due to the high temperatures of the combustion process and sufficient oxygen for the thermal reactions of NO_x formation. At the site where α = 0.95-0.94, the NO_x concentration is slightly lower, although the combustion temperature is maximum. This is due to the lack of oxygen.

Therefore, different changes in the composition of a mixture with a particular system will be reflected in the concentrations of each harmful substance at the outlet of the three-component catalytic converter. As can be seen from Fig. 3b, in idle modes, the efficiency of CO and C_mH_n neutralization is in the range of 86…100% for the injection system, and with the carburetor system 13…25%, respectively.

Under load conditions of enrichment of the air-fuel mixture, the neutralization of the harmful substances CO and C_mH_n when using the injection system is 79...100%, with a carburetor system, respectively 45...78%. At full load, α = 0.95-0.94 enrichment occurs, neutralization for both systems is reduced. The efficiency of neutralizing NO_x in the entire range of the load characteristic increases from 69% to 91% with the injection system, which is explained by an increase in the temperature of the exhaust gases (tvg). In addition, the operation of an engine with a carburetor system provides less NO_x neutralization efficiency (34...81%). This is due to the enrichment of the composition of the mixture.

4. Conclusion

The presented literature stage shows that the automotive industry is currently undergoing enormous transformations, and this is visible in the development of internal combustion engines and fuels to power them. Work on their improvement and operating conditions is ongoing all over the world. One of the important aspects of vehicle operation is taking care of the proper technical condition of the drive systems, which results in lower fuel consumption and limiting the emission of harmful gases into the atmosphere from internal combustion engines.

This article presents a review of the literature as well as a description of the test stand and methodology for testing emissions from a compression-ignition engine and comparative tests of a spark-ignition engine equipped with a standard fuel supply and injection system in a passenger car. It has been shown that the engine powered by the injection system shows lower emission of the standard exhaust components compared to the carburetor fuel supply.

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