Ensuring reliability of electronic control of engine fuel supply subsystem in operation

Y Bazhenov¹,³, M Bazhenov¹ and V Kalyonov²

¹Vladimir State University named after Alexander and Nikolay Stoletovs, Gorky St. 87, Vladimir, 600000, Russia
²Dealer center Peugeot, Kuibyshev St. 24A, Vladimir, 600035, Russia
E-mail: ¹ bagenovyv@mail.ru

Abstract. The paper presents results of a study of operational reliability of electronic control of an automotive engine fuel supply subsystem. Impacts on the structural elements of the subject subsystem stipulated by physical and chemical processes of heat transfer and dissipation, absorption of magnetic and electric fields, wear and tear, etc., leads to occurrence of various kinds of damage in them. Causes of the subsystem getting inoperable and the effect of failures of its elements on the engine operation are revealed. Considerable attention is paid in the paper to the diagnostics of the technical state of order of the subsystem which must be performed in scheduled car maintenance intervals in accordance with the developed method and algorithm. The deviation of the fuel pressure in the fuel rail from the setpoint in the electronic control unit was taken as the diagnostic parameter for the evaluation of the technical condition of the subsystem. Using Microsoft Excel, an analytical equation was selected that describes the dependency of the diagnostic parameter deviation versus the running time of the vehicle allowing for the substantiation of its rated values. The results of the performed studies were tested and introduced into the technological processes of maintenance and repair of Peugeot cars of “Auto Tract Peugeot” dealership, Vladimir City.

Introduction
The operation of a modern internal combustion engine is controlled by an electronic engine control system (EECS), which ensures high technical and economic performance and compliance with environmental requirements to exhaust gas toxicity. During the operation, various types of damage and faults inevitably occur in the EECS (violation of adjustments, change of electrical characteristics, corrosion failure of contacts, insulation damage, etc.). The on-board self-diagnostics system of the electronic engine control system cannot provide its reliable operation, since the electronic control unit stores the fault code only when any of the diagnostic parameters exceeds the rated value set in the software, i.e. when the fault has already occurred. Untimely detection and elimination of damages leads to engine malfunction, full or partial loss of serviceability (failure). To reduce the number of failures, to detect hidden damage and to ensure the required level of reliability of the electronic control systems, it is necessary to monitor the technical condition of their elements during routine maintenance of motor vehicles at car service workshops.

Overview of previous works
The issues of ensuring the operational reliability of the electronic control of the fuel supply (FS) subsystem are poorly studied. The performed studies are mostly aimed at the development of diagnostic methods for individual EECS elements, studying the causes of malfunctions and their impact on the technical and economic performance of the engine, maintenance and repair methods of internal combustion engines equipped with control systems [1-6]. In the adopted maintenance regulations of cars, no monitoring of the technical condition of the elements of the FS subsystem is envisaged. This leads to concealed unsolved
failures in a number of vehicles after routine maintenance, which entails an increase in the number of operational failures. The analysis of literary sources shows that 30 to 38% of failures of gasoline engines occur exactly due to damages of EECS structural elements [7-10]. Considering that, studies aimed at ensuring the reliable operation of electronic engine control systems are relevant and of great practical importance.

Methods

The EECS is a complex technical system of a motor vehicle containing several dozen structural elements, which, in terms of their functional purpose and diagnostical convenience, are advisable to subdivision into several subsystems. The number of subsystems is based on the available number of individual diagnostic parameters depending on the complexity of the EECS used [9, 11].

In the present paper, the selected DUT, 1.6 THP Turbo Tiptronic (110 kW) EECS of Peugeot 408, is divided into 4 subsystems: fuel supply control, air supply control, valve timing phase control and exhaust gas toxicity control. Studies carried out in the maintenance shop of Peugeot dealership in Vladimir during maintenance, repair and diagnostics of electronic control systems of gasoline engines have shown that the fuel supply subsystem is the least reliable subsystem of EECS. The results of the studies of the operational reliability of this subsystem are given in Table 1 and in the form of bar graphs and their theoretical smoothing distribution curves of running time distribution before failure in Figure1.

The shapes of the curves, as well as the calculated values of the coefficient of variation v show that the distribution of the running times before failure of the parts of the FS subsystem are adequately described by Weibull distribution. Testing the hypothesis for fitting of the experimental data into this distribution using Pearson's chi-squared test confirmed its validity.

Table 1. Statistical estimates of the numerical reliability characteristics of the fuel supply subsystem

| Structural element                      | Mean time to failure, thousand km | Mean square deviation | Coefficient of variation |
|-----------------------------------------|----------------------------------|-----------------------|-------------------------|
| 1. Electric gasoline pump               | 119.3                            | 68.35                 | 0.57                    |
| 2. High pressure fuel pump (with fuel pressure regulator) | 90.6                             | 56.84                 | 0.63                    |
| 3. Fuel injector                        | 125.8                            | 46.39                 | 0.37                    |
| 4. Fuel pressure sensor                 | 185.3                            | 117.06                | 0.63                    |

![Figure 1](image-url)

**Figure 1.** Bar graphs (1) and theoretical curves (2) of running time to failure distributions of structural elements of the fuel supply subsystem: a) electric gasoline pump; b) high pressure fuel pump; c) fuel injector; d) fuel pressure sensor
The operation of the elements of the FS subsystem is based on the use of electrical, electromagnetic, electronic, mechanical and other processes. In the parts of the subsystem, there are processes of heat transfer and dissipation, absorption of magnetic and electric fields, wear, etc. The impact of the listed processes leads to the occurrence of various kinds of damage in the structural elements of the FS subsystem and, in case of untimely troubleshooting, to a loss of operability (Table 2).

**Table 2.** Causes of FS subsystem failures and their impact on engine operation

| Subsystem element | Causes of element failure                                                                 | Failure effect                                                                 |
|-------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| 1. Electric gasoline pump | Stall of the gasoline pump motor armature, hanging and wear of brushes, destruction of insulation and inter-turn short circuit in the pump motor winding, collector wear | The engine cannot be started because the fuel supply to the engine cylinders is blocked |
| 2. High pressure fuel pump | Failure of tightness of the shut-off valve of the pressure regulator due to its contamination, destruction of insulation and inter-turn short circuit in the pressure regulator winding, wear of pump plunger pairs | Reduction of engine power down to 80%, increase of fuel consumption by 18-20% and increase of emissions of harmful substances with exhaust gases by 8-10% |
| 3. Fuel injector | Insulation destruction and inter-turn short circuit in electromagnetic valve winding, accumulation of lacquer deposits and coking of nozzle metering elements reducing the section of calibration channel | Decrease in power by 20-25%, increase in fuel consumption by 17-19%, increase in emissions of harmful substances by 12-15%, unstable operation of ICE in idle mode |
| 4. Fuel pressure sensor | Contamination of sensor's sensing element, sensor solder connection contact violation | Reduction of engine power by 25-30%, increase of fuel consumption by 12-15% and emissions of harmful substances by 5-7% |

As follows from the table, a significant part of the failures of the structural elements of the FS subsystem having the excitation winding is associated with the destruction of its insulation, which undergoes natural wear and aging due to temperature changes, vibrations, moisture, etc. Short-circuits of the winding to the housing occur due to local deterioration of insulation which occurs due to friction of winding turns between each other or against the housing, as well as to the insulation fouling.

The analysis of the obtained results given in the table shows that the technical condition of the structural elements of the FS subsystem has a serious influence on the engine operation. In case of a failure, for example, of the electric gasoline pump, the engine gets completely inoperable, since the fuel supply to the cylinders is blocked. The technical condition of the high-pressure fuel pump has a significant impact on the performance of the engine. When various kinds of mechanical damages occur in it, the engine power goes down to 80%, the fuel consumption and the emissions of harmful substances with the exhaust gases (carbon monoxide (CO), hydrocarbons (CH), nitrogen oxides (NOx)) are significantly increased.

The main reliability indicators of any technical object, along with the mean time to failure, are the probability of its failure-free operation $P(t)$ and the failure rate $\lambda(t)$ which clearly show the dependence of the failures on the running time [12, 13]. Statistical estimates of these indicators for the elements under test are given in Table 3.

While analyzing the data given in the table, it is possible to draw certain conclusions on the operational reliability of the parts of the FS subsystem under test. For the initial running time intervals 0 to 90 thousand km, the probability of the parts failure, with the exception of the high-pressure fuel pump, is at a sufficiently high level. By the running time interval of 120-150 thousand km, the probability of failure-free operation of almost all elements of the FS subsystem is significantly reduced. Up to that running time, operational damages occur and accumulate in these elements (wear, lacquer deposits and coking of metering elements, deterioration of insulation in the windings, etc.) which reduce the effi-
ciency of their operation and, in the long run, the inevitable loss of operability. Almost all parts of the FS subsystem get completely worn out within a running time of 270 thousand km.

Table 3. Indicators of fuel supply subsystem elements failure-free operation by running time intervals

| Indicator                  | Running time interval, thousand km. | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | 150-180 | 180-210 | 210-240 | 240-270 |
|----------------------------|------------------------------------|------|-------|-------|--------|---------|---------|---------|---------|---------|
| Electric gasoline pump     | $P(t)$                             | 0.98 | 0.97  | 0.94  | 0.63   | 0.37    | 0.15    | 0.06    | 0.03    | 0.01    |
| $\lambda(t) \times 10^{-4}$|                                    | 0.40 | 0.41  | 1.26  | 12.19  | 15.11   | 22.25   | 27.78   | 37.04   | 66.67   |
| High pressure fuel pump    | $P(t)$                             | 0.98 | 0.94  | 0.56  | 0.25   | 0.14    | 0.08    | 0.04    | 0.03    | 0.01    |
| $\lambda(t) \times 10^{-4}$|                                    | 0.79 | 1.22  | 16.66 | 26.06  | 18.18   | 17.54   | 26.66   | 33.32   | 64.87   |
| Fuel injector              | $P(t)$                             | 0.98 | 0.98  | 0.95  | 0.89   | 0.80    | 0.58    | 0.25    | 0.05    | 0.01    |
| $\lambda(t) \times 10^{-4}$|                                    | 0.52 | 0.52  | 1.06  | 10.59  | 20.29   | 24.76   | 31.11   | 40.07   | 67.98   |
| Fuel pressure sensor       | $P(t)$                             | 0.98 | 0.98  | 0.95  | 0.89   | 0.80    | 0.58    | 0.25    | 0.05    | 0.01    |
| $\lambda(t) \times 10^{-4}$|                                    | 0.52 | 0.00  | 1.06  | 2.22   | 3.64    | 10.37   | 27.16   | 45.61   | 65.67   |

The graphical interpretation of the change in the statistical estimates of the failure intensity $\lambda(t)$ and the probability of failure-free operation $P(t)$ by $t$ running time is shown based on the example of the electric gasoline pump and the fuel pressure sensor (Figure 2).

The completed studies of the operational reliability of the structural elements of the subsystem show that the process of their technical condition change depending on the running time of the car is smooth and monotonous, leading to the occurrence of so-called gradual failures. For such failures, the change of a technical condition parameter is analytically well described by an entire rational function of the n-th order [14–16].

Based on the results of processing of the statistical data of the operational reliability of the components of subsystem under analysis, the following analytical dependencies of the change in the intensity of their failures $\lambda(t)$ versus the running time were obtained:

$$
\lambda_{gp}(t) = 0.199t^3 - 1.877t^2 + 8.820t - 9.035;
\lambda_{fp}(t) = 0.521t^3 - 7.139t^2 + 32.210t - 29.460;
\lambda_{fi}(t) = 0.126t^3 - 0.873t^2 + 5.521t - 6.392;
\lambda_{ps}(t) = 0.152t^3 - 0.478t^2 - 0.750t + 2.139,$$

where $\lambda_{gp}(t)$, $\lambda_{fp}(t)$, $\lambda_{fi}(t)$, $\lambda_{ps}(t)$ are the failure rates of the electric gasoline pump, high-pressure fuel pump, fuel injector, fuel pressure sensor, respectively; $t$ is the vehicle running time.
In order to ensure reliable operation of the FS subsystem and to reduce the cost of repairs after failures, it is necessary that most of them should be prevented during routine maintenance of motor vehicles with a preliminary assessment of the technical condition of the subsystem using diagnostic methods.

The deviation of the fuel pressure in the fuel rail $P_{fp}$ from the setpoint in electronic control unit (ECU) was assumed as the diagnostic parameter characterizing the technical condition of the subsystem. The limit value $P_{lp}$ and the rated value $P_{np}$ of this parameter are set on based on studies of the engine operation processes during the design of EECS by manufacturers and are given in the technical regulations for after-sales maintenance and repair of Peugeot motor vehicles [17]: $P_{lp} = 9$ bar; $P_{np} = 3$ bar.

It is advisable to use the permissible value of $P_{pp}$ parameter rather than the limit value, as a standard, when performing control and diagnostic works to evaluate the technical condition of the FS subsystem in automotive service workshops. To determine it, it is necessary to find out the regularity of change of the fuel pressure deviation from the ECU setpoint versus vehicle running time.

The expiry of the service life assigned to the subsystem by its design is stipulated by the gradual accumulation of various damages in their elements (wear, corrosion, etc.). The development of such damages depending in the course of time or along with the running time is smooth, monotonous, leading to occurrence of gradual failures, therefore, with some probability, the change in the technical condition parameter by running time $t$ can be described by the power function [18, 19, 20]:

$$y(t) = y_n + vt^\alpha,$$

(2)

where $y_n$ is the rated value of the technical condition parameter; $v$ is the intensity of the parameter change along with the running time; $t$ is the running time of the DUT; $\alpha$ is the exponent determining the dependence of parameter $y$ on running time $t$.

The change in the analog diagnostic parameter versus the running time for most units and assemblies of a motor vehicle is described by the same functions as the parameters of the technical condition. The analytical equation selected using Microsoft Excel, describing the change in the diagnostic parameter $P_{fp}$ versus the running time, will have the following appearance:

$$P_{fp}(t) = P_{nfp}(t) + vt^\alpha = 3 + 0.044t^{1.03},$$

(3)

where $P_{nfp}(t)$, $P_{fp}(t)$ are, respectively, the rated and the current values of diagnostic parameter $P_{fp}$.

The exponent $\alpha$ and intensity of change of the diagnostic parameter $v$ versus the running time are determined experimentally, based on the processing of the experimental data on the operational reliability. The graphical presentation of the analytical equation is given in Figure 3.

![Figure 3](image_url)

**Figure 3.** Graph of $P_{fp}$ diagnostic parameter change by operating time: $P_{nfp}$, $P_{lp}$, $P_{pp}$ – nominal, limit and permissible values of diagnostic parameter; $t_{av}$ – average time between failures

Knowing the periodicity of the vehicle diagnostics (for Peugeot, $t_m = 20$ thousand km), the permissible value of the diagnostic parameter $P_{pp}$ is determined from the expression
Fault detection and localization in the fuel supply subsystem is performed in accordance with the algorithm developed and tested in the Peugeot dealership of Vladimir (Figure 4).

After the elimination of faults detected as a result of diagnostics, the fuel pressure $P_{fp}$ deviation in the rail is checked again. If its value does not exceed the permissible standard (7 bar), the technical condition of the FS subsystem is deemed restored guaranteeing its failure-free operation till the next maintenance is carried out.

\[
P_{fp} = v \left( \frac{a_{fp}}{v} - t_{in} \right) = 0.044 \left( \frac{1.03}{0.044} - 20 \right) = 7 \text{ bar}.
\]

**Figure 4. Algorithm of fuel supply subsystem diagnostics**
Conclusions
The results of the study demonstrate that failures of the fuel supply subsystem lead to a significant worsening of the engine performance and an increase in emissions of harmful substances into the environment. To ensure reliable operation of the structural elements of this subsystem, it is necessary to carry out diagnostics of their technical condition with the periodicity of the scheduled vehicle maintenance. The FS subsystem diagnostics technology proposed in the paper makes it possible to significantly reduce the number of its failures during the operation due to the timely detection of damage occurring in it which remain concealed to the on-board diagnostics system of the vehicle.

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