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CHARACTERISTICS OF THE DIAGNOSIS PROCESS OF THE HIGH PRESSURE PUMP ON THE EXAMPLE OF A SPARK IGNITION ENGINE

Piotr SLIŻ
University of Gdańsk, piotr.sliz@ug.edu.pl

Summary
The basic objective of the article was to identify inference algorithms (rules) in the diagnosis process of high pressure pumps (HP) on the example of gasoline engine units, designated as EP (THP). For the needs of the main objective, a partial goal was assigned. It was to characterize the symptoms and diagnostic codes indicating the malfunction of the high pressure pump. As a result of empirical proceedings, the results of the analysis of completed repairs of the high pressure fuel system were presented, then, based on the technical documentation and observation of the course of diagnostic activities in workshop conditions, the HP pump diagnostic process was recreated on the example of the tested EP unit. In addition, as a result of the study, factors shaping the correct implementation of the HP pump diagnosis process were identified. This study may be an incentive for a more in-depth analysis of the methodology for diagnosing low and high pressure fuel circuits in spark-ignition engines.

Keywords: high pressure pump diagnostic, HP pump, fuel system, petrol engine, gasoline engine.

CHARAKTERYSTYKA PROCESU DIAGNOZOWANIA POMPY WYSOKIEGO CIŚNIENIA PALIWA NA PRZYKŁADZIE SILNIKA O ZAPŁONIE ISKROWYM

Streszczenie
Celem podstawowym artykułu była identyfikacja algorytmów (reguł) wnioskowania w procesie diagnozowania pomp wysokiego ciśnienia paliwa (HP) na przykładzie benzynowych jednostek silnikowych, oznaczonych jako EP (THP). Na potrzeby realizacji celu głównego przyporządkowano cel cząstkowy. Było nim scharakteryzowanie symptomów i kodów diagnostycznych wskazujących na usterkę pompy wysokiego ciśnienia paliwa. W rezultacie przeprowadzonego postępowania empirycznego przedstawiono wyniki analizy zakończonych napraw układu wysokiego ciśnienia paliwa, następnie, w oparciu o dokumentację techniczną i obserwację przebiegu działań diagnostycznych w warunkach warsztatowych odtworzono proces diagnostyki pomp HP na przykładzie badanej jednostki EP. Ponadto w rezultacie badania zidentyfikowano czynniki kształtujące poprawną realizację procesu diagnozy pomp HP. Niniejsze opracowanie może stanowić asumpt do głębszej analizy metodyki diagnozy obiegów niskiego i wysokiego ciśnienia paliwa w silnikach o zapłonie iskrowym.

Słowa kluczowe: diagnostyka pompy wysokiego ciśnienia, pompa paliwowa HP, system paliwowy, silnik benzynowy

1. INTRODUCTION

The development of technology in the construction of fuel injection systems in passenger cars with the simultaneous market demand for more and more economical propulsion unit solutions was one of the reasons for the implementation of high pressure fuel systems in spark-ignition engines [1. 3]. As a consequence, the design solutions of fuel systems were transferred from compression-ignition (diesel) engines to spark-ignition engines (SI). One of the widely used units of this type on the European market today are engines bearing the EP trade symbol, also identified as THP[1] (turbo high pressure) with a capacity of 1598 cm^3. They were used by the BMW Group PSA Group[2].

The issue of the application and concept of improvement of high pressure fuel systems, in particular in compression ignition engines (ZS), has been widely discussed in the literature [2, 9, 10. 13, 15, 18]. Fuel injection has been widely described in the literature on the subject in terms of ecology [8, 14]. The analysis of the phenomenon of high pressure and its impact on fuel injection physics is described in [7]. Despite the few publications on SI engines, it can be concluded that the characteristics of high pressure fuel systems and attempts to reproduce the diagnosis process of high pressure pumps (HP) in spark-ignition engines is a cognitive gap.

The reason for the implementation of empirical proceedings was the observation, under workshop

[1] The THP, EP6CDT and EP designations in this study will be used interchangeably.
[2] The model calculation presents models with units with different characteristics and emission standards (Euro 5 and Euro 6). The overview of installed units includes engines marked with symbols: EP6DT, EP6DTS, EP6CDT, EP6CDTM, EP6CDTMD, EP6DTS, EP6CDTS, EP6XDTX, EP6FDTX, EP6FDTR and EP6CDTR. In the BMW Group, the engines were marked with the N13 and N18 symbols.

conditions, of the process of diagnosing high pressure pumps in the THP engines, as a result of which three different inference algorithms were identified based on technical documentation and workshop practice in authorized service centres. The main goal of the article was to identify inference algorithms (rules) in the process of diagnosing HP pumps in the EP engines (THP). For the purpose of achieving the main goal, a partial goal was formulated, which was to present the characteristics of symptoms and diagnostic codes indicating a fault of the high pressure pump. The subject of the study in this article was the gasoline direct injection (GDI) system. In the literature, other designations can be observed that are used, for example, by the Volkswagen Group – FSI [17, 5, 6] (fuel stratified injection) or TFSI [4, 19] (turbocharged fuel stratified injection). At this point, it should be emphasized that the GDI technology has been described in both Polish and foreign subject literature [4]. The unit with the GDI system on the example of the Volkswagen brand has been described in [12].

The research problem was formulated in the form of two research questions (RQ). RQ1: What factors determine the effective diagnosis of the HP pump in the EP engines? RQ2: What is the process of diagnosing high pressure pumps in the tested type of engine?

Making the above synthesis, the main thesis of the article was formulated. The methodology for diagnosis high pressure pumps in EP engines requires a combination of computer and mechanical diagnostics.

The research focused on the executive element – a high pressure pump, which main function is to generate high fuel pressure and supply fuel to the injectors through the fuel pressure manifold. This means that the test subjects were passenger cars[3] equipped with EP6CDT engines, while the subject of the study in a broad scope was a high pressure fuel system, while in the narrow scope – the HP pump used in three models. The article uses research methods such as literature review, participant observation, semantic analysis of the text and statistical methods.

2. CHARACTERISTICS OF THE OBJECT AND SUBJECT OF THE EMPIRICAL PROCEDURE

The subject of the study was the circulation of high pressure fuel system in SI engines with a capacity of 1598 ccm3 (EP6CDT). In order to clarify, the object of the study were road vehicles, manufactured by the X manufacturer. They were classified according to the model in which the above-mentioned power units were installed (Tab. 1).

Table 1. Classification of the tested units according to the models

Model	Number	Percent	Accumulated percentage
Model A	2	2,99%	2,99%
Model B	5	7,46%	10.45%
Model C	2	2,99%	13,43%
Model D	**36**	**53,73%**	**67,16%**
Model E	17	25,37%	92,54%
Model F	5	7,46%	100.00%

Source: own study.

At this point, it should be emphasized that during the production period of the A−F models (tab. 1), drive units with a capacity of 1598 ccm2, diversified in terms of characteristics, were implemented in them. In the empirical proceedings, one of the models presented in tab. 1 was chosen. The decision was made to choose model D, which unit was characterized in tab. 2. This choice was supported by the largest number of repairs carried out, which constituted 53.73% of the entire surveyed population (tab. 1). This means that the generalizing conclusions presented in the work were formulated based on completed repairs carried out in 2016.

Table 2. Characteristics of the EP6DT engine

Parameter	Value	Unit
Engine type	EP6DT	-
Type	5FR	-
Engine displacement	1598	[cm^3]
Maximum power	115	[kW]
Diameter of the piston	77	[mm]
Piston stroke	85,8	[mm]
Rotation speed (max speed)	6000	[rpm]
Maximum torque	24	[daNm]
Speed of maximum torque	1400	[rpm]
Weight	117	[kg]

Source: own study based on materials obtained during the study.

The EP engine performance curve is shown in fig. 1

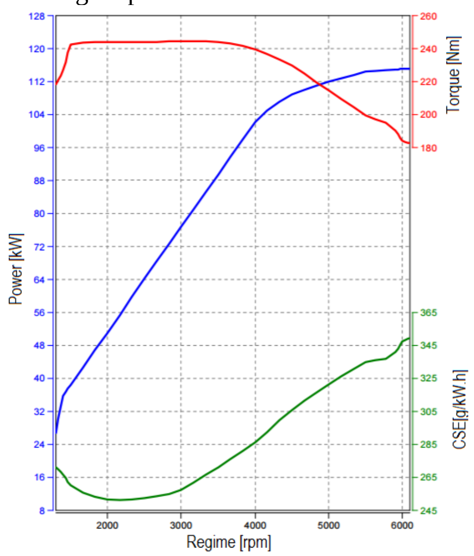

Fig. 1. Performance curve of the EP engine [20]

[3] According to the classification of road vehicles, passenger cars should be understood as a group of car vehicles belonging to the group of motor vehicles. In addition, according to the division formulated by the United Nations Economic Commission for Europe (UN ECE), the vehicles in question are classified in the category designated by the M1 symbol; [11].

The fuel system of the tested unit was classified due to low and high fuel pressure circuit. The first includes the following elements: fuel tank, internal and external fuel vapours absorbent and a pump with a measuring (indicator) module. In turn, the high pressure circuit was designed using: a manifold supplying gasoline injectors, gasoline injectors, Schräder valve, tank venting solenoid valve, high pressure fuel sensor and HP pump. The nominal value of the fuel pressure in the system is: 5 0.5 [bar]. The HP pump defined as the executive element of the high pressure circuit of the fuel system is presented in fig. 2−3. The direct injection system in this unit was manufactured by the Bosch company and it was marked with the MED. 17.4 symbol. Fig. 2 shows the HP pump drive (1), oil pressure valve (2) and high pressure fuel solenoid valve (3). It should be mentioned here that the pump is driven by the suction camshaft.

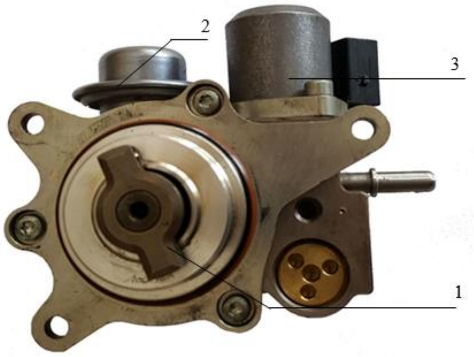

Figure 2. Characteristics of the Siemens high pressure pump construction from the pump drive side
Source: Own study.

Figure 3. Characteristics of the construction of a Siemens high pressure pump from the side of the low fuel inlet
Source: Own study.

On the other hand, fig. 3 presents the test object from the low fuel pressure inlet side (4), including the high pressure fuel outlet (5) and the two-valve connector supplying the solenoid valve (6).

3. ORGANIZATION AND CHARACTERISTICS OF THE RESEARCH PROCEDURE

In order to map the process of diagnosing the high pressure fuel pump, an attempt was made to carry out a quantitative test on a group of units selected probabilistically for repairs carried out in model D (tab. 1). In the sample selection, simple random sampling was selected. The randomized sample generator prepared in a Microsoft Excel 2016 was used in drawing the study units. The population in the sampling frame amounted to 36 units. To clarify, the study assumed a maximum error not exceeding +/- 15%, with a confidence level = 0.9[4].

$$n = \frac{\hat{p}\cdot(1-\hat{p})}{\frac{d^2}{z^2_{\alpha/2}} + \frac{\hat{p}\cdot(1-\hat{p})}{N}} \quad (1)$$

where:
n = minimum sample size
$N =$ population size (the number of all repairs related to replacing the HP pump on the market under consideration for the X brand in 2016)
p = assessment of the unknown standard deviation value in the population,
d = standard error
$z_{\frac{\alpha}{2}}$ = value of the random variable Z with a standard normal distribution, such that
$P(|Z| \leq z_{\frac{\alpha}{2}}) = 1 - \alpha$.

The sample size was estimated based on the first record. It amounted to n ≥ 20. As a result, a list of 20 repairs was obtained, which were systematized in terms of the repair date (RD), production date (PD), warranty start date (WSD), mileage and vehicle age from the warranty start date (Age_U) and vehicle age from the production date (Age_R). It should be emphasized here that the age of the vehicle is understood as the number of months from the date the vehicle was released to the final customer (Age_u) or production (Age_r) until the failure was reported.

Fig. 4 presents the characteristics of the HP pump failure taking into account the vehicle mileage value (4a) and vehicle age, estimated in weeks of operation (difference in the number of weeks between the date of fault identification and the date of sale of the car) (Age_U variable).

In order to expand, an attempt was made to analyse the correlation between the *Mileage* and *Age_U* variables. First, the variables were tested for distribution normality using the Kolmogorov-Smirnov test with the correction of the Lilliefors significance[5]. For each variable, the distribution is consistent with the Gaussian distribution (normal distribution). Summarizing the above, it was estimated that there is a strong positive correlation (0.636) between the Age_U variable and the Mileage variable (for $p < 0.05$). Based on the obtained correlation values, a decision was made to accept the variables *Age_U* (Zmn4) and *Mileage* (Zmn5) for further research.

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[4] The fraction p = 0.5 is taken as the maximum value of the product $\hat{p}\cdot\hat{q} = (\hat{p}\cdot(1-\hat{p})$; [16].
[5] The small size of the sample was in favour of choosing the Kolmogorov-Smirnov test with the correction of Lilliefors significance.

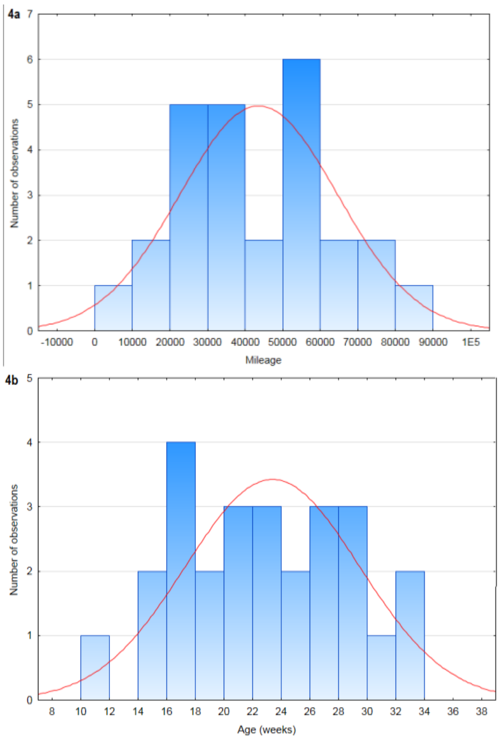

Fig. 4. Histogram of the HP pump failure due to vehicle mileage (4a) and age (4b)
Source: own study based on the study carried out in 2017.

4. ANALYSIS OF USER REPORTS CONCERNING FAULTS OF THE HIGH SYSTEM OF THE HP PUMP

First of all, the symptoms reported by users of the D model related to the failure and replacement of the HP pump were referred to. Table 3 lists the most frequently occurring phrases in the tested symptom sample (table 3).

Table 3. Comparison of the severity of the occurrence of parameters in the examined group of objects

Symptoms of damage in the users' reports*	Number of occurrences	Percent
Self-diagnosis indicator	19	73.08%
Lack of power	8	30.77%
Reduced power	4	15.38%
Uneven engine work	3	11.54%
Loses power when accelerating	2	7.69%
Reduced engine power	2	7.69%
Engine vibration	2	7.69%

*Symptoms developed on the basis of vehicle users' reports in repair orders.
Source: own study based on the study carried out in 2017.

On this basis, a conclusion was formed that in the studied repair group, the dominant reports were related to the following phrases: engine control and lack of power. As a result of the analysis of customer reports, presented in table 3, the phrases were narrowed down and classified into three parameters: self-diagnostics, power and vibration.

5. RESEARCH RESULTS AND DISCUSSION

Based on the technical documentation made available during the test and the analysis of random repairs carried out for the D model, an attempt was made to reconstruct the process of diagnosing the high pressure pump in the EP engine (Figure 5). The Adonis NP version 4.1 software was used to reconstruct the process.

When balancing the previous information, for control activities characterized in the diagnosis process map (Figure 5), the marked control values should be determined: the permissible value of the fuel system pressure is the range of Z = <4.5;5.5> [bar], the permissible value of ethanol in the collected fuel sample is 10%, the nominal length of the spring is 27 [mm]. Values exceeding the above ranges determine the need to replace the HP pump. In addition, table 4 makes a distinction between the tested repair group due to the inference algorithm in the diagnosis process. To be more precise, algorithm 1 was identified for repairs with the confirmed error code P0087, while the implementation of algorithm 2 was determined by the occurrence of a pair of selected errors. They were P1336, P1337, P1338, P1338 and P1340. (tab. 4). Algorithm 3 includes repairs that were not qualified for the algorithm of procedure 1 and 2. Table 5 summarizes the error codes identified based on the complete repair orders in authorized service stations[6].

Table 4. Types of algorithms for diagnosing HP pumps in the repair process in the research sample

Algorithm of conduct*	Identified number	Percentage in the study
S1	14	70%
S2	4	20%
S3	2	10%
Result	20	100%

*The study recreated three different inference algorithms in the diagnosis process. They have been verified against the technical documentation, and only S1 and S2 were found to comply with the repair methodology developed by the manufacturer.
Source: Own study based on the study carried out in 2017.

In order to confirm the classification of inference algorithms presented in table 4 in the diagnosis process for completed repairs, repairs with the manufacturer's technical documentation were verified. As a result, out of the tested repair attempt, in 10% of repairs criteria were not verified correctly. In view of the above, for the further part of the procedure, repairs were selected with correctly identified algorithms of conduct 1 and 2. The analysis was based on the error characteristics

[6] The repair order in the tested units is a document on the basis of which an external or internal customer reports faults and/or the scope of activities to be performed by the ASO. Depending on the type of reported fault, repair orders can be divided into: paid, warranty, internal and body shop. Each repair order, regardless of its type, has a unique number.

presented in table 5. Next, diagnostic error values for error P0087 read by the computer were summarized and characterized (Tab. 6). Based on the reconstructed diagnosis process of the high pressure fuel system (Fig. 5), mechanical assessment criteria for repairs characterized in table 6 were verified. In none of the examined cases of diagnosis using algorithm 1. the fuel pressure value outside the normative range, damage to the driver, as well as the exceeded value of the spring length in the HP pimp compensator were confirmed. In the tested repair sample, the measured fuel pressure was in the range of 5−5.4 [bar]. In turn, the measurement of the spring length in the compensator was within the established tolerances of 27−29 [mm]. These were the criteria that determined the need to replace the HP pump in accordance with the manufacturer’s technical documentation. To clarify, it should be emphasized that the data presented in table 6 contain parameters during the occurrence of the specified error code. This means that the values of individual parameters have been recorded at the time when the selected parameters exceeded the tolerance range. Parameter values for selected repairs in table 6 only apply to the P00087 error. Parameters accompanying the P0087 error in addition to those indicated in table 6, were as follows: mileage, setpoint of the intake phase shifter’s position, enrichment setpoint, input mixture correlation coefficient, intake camshaft phase shifter’s position, crankshaft target adaptation at emptying (1− done, 0− not done), measured inlet pressure, setpoint filling, intake air temperature, setpoint pressure in the gasoline manifold, pressure in the gasoline manifold and fuel level (tab. 9).

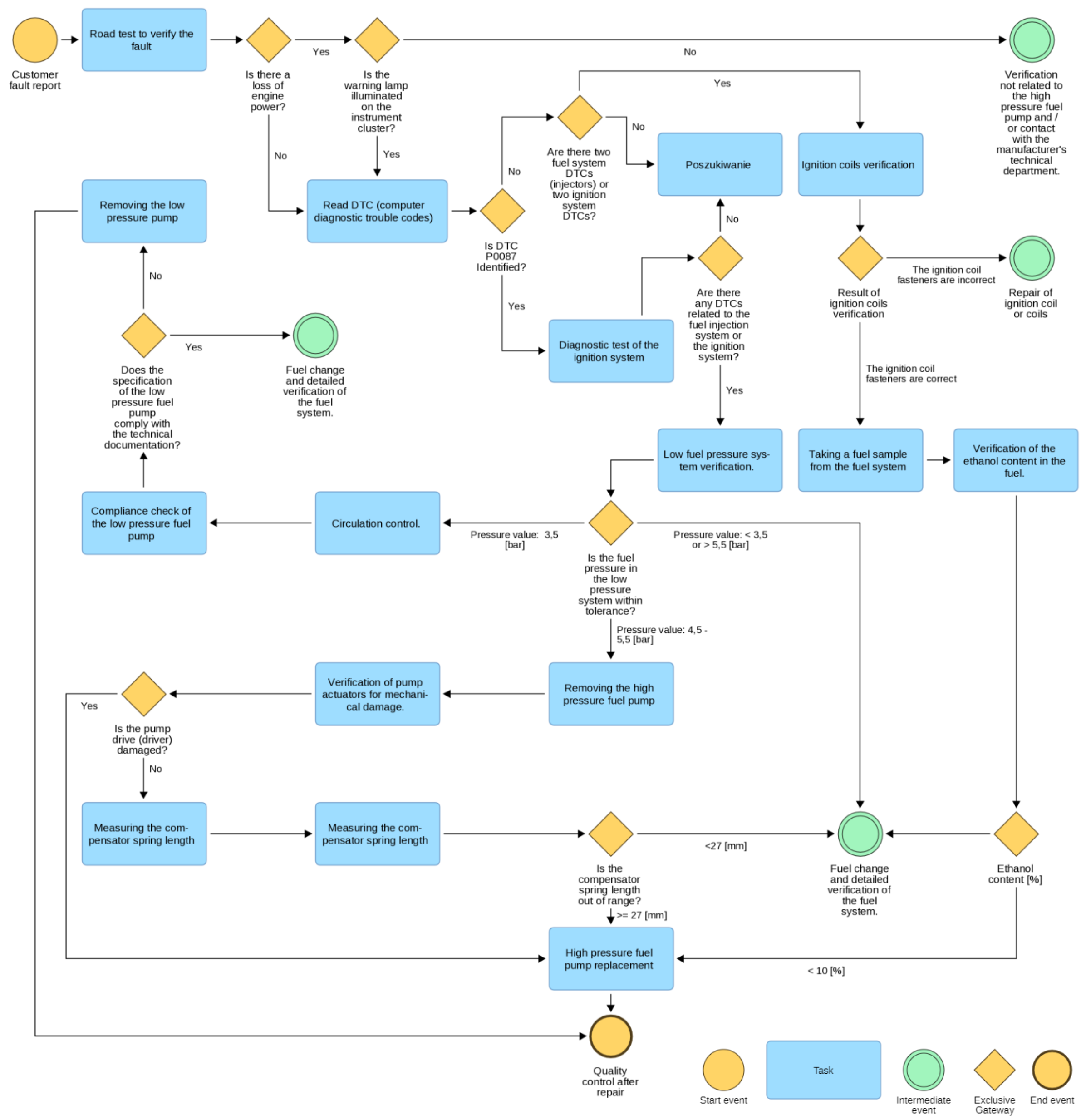

Fig. 6. Recreated course of activities in the process of diagnosing the high pressure pump in THP engines
Source: own study based on technical documentation and research using the Adonis program.

Table 5. List of selected faults used in the diagnosis of HP pumps in THP engine

<table>
<tr><th>Error codes / Parameter</th><th>P0087</th><th>P1337</th><th>P1338</th><th>P1339</th><th>P1340</th><th>P0171</th><th>P0172</th><th>P1385</th></tr>
<tr><td>Characteristics of the diagnostic code</td><td>The value of the pressure measured in the injection manifold is lower than the set value</td><td>Ignition loss, cylinder 1</td><td>Ignition loss, cylinder 2</td><td>Ignition loss, cylinder 3</td><td>Ignition loss, cylinder 4</td><td>Regulation of the composition of the mixture, blend for poor</td><td>Regulation of the mixture composition, mixture too rich</td><td>Super detonation combustion</td></tr>
<tr><td>Self-diagnosis indicator</td><td colspan="8">Yes</td></tr>
<tr><td rowspan="8">The main possible symptoms felt by the client</td><td rowspan="4">Engine speed is suspended</td><td colspan="4">Starting impossible</td><td rowspan="2">Excessive fuel consumption.</td><td rowspan="2">Ignition loss during acceleration</td><td rowspan="2">Lack of power</td></tr>
<tr><td colspan="4">Engine starting is difficult</td></tr>
<tr><td colspan="6">Idling unstable</td><td></td></tr>
<tr><td colspan="4">Idle speed too high</td><td></td><td>Turning the engine off at idle</td><td></td></tr>
<tr><td colspan="5">Lack of power</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3"></td><td colspan="4">Engine vibration</td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Non-standard emissions</td><td></td></tr>
<tr><td colspan="4">Excessive fuel consumption</td><td></td><td>Lack of power</td><td></td></tr>
<tr><td rowspan="16">Additional areas</td><td>HP pump</td><td colspan="6">Electric harness</td><td>Engine oil level</td></tr>
<tr><td>Low pressure fuel circuit</td><td colspan="4">Spark plugs</td><td>Intake manifold</td><td>Intake manifold</td><td>Engine cooler</td></tr>
<tr><td rowspan="14"></td><td colspan="4">The ignition coil</td><td colspan="2">Front oxygen probe</td><td>Water pump</td></tr>
<tr><td colspan="6">Fuel injector</td><td>Water pump</td></tr>
<tr><td colspan="4">Engine calculator (module)</td><td colspan="2">Air filter</td><td>The accessory drive belt</td></tr>
<tr><td colspan="3">Engine compression</td><td>Turning off the enrichment regulation</td><td colspan="2">Tank venting solenoid</td><td>Cooling distribution block</td></tr>
<tr><td rowspan="10"></td><td rowspan="10"></td><td rowspan="10"></td><td rowspan="10"></td><td colspan="2">Timing setting</td><td>Control thermostat</td></tr>
<tr><td colspan="2">Water temperature sensor / Coolant distribution block</td><td>Turbocharger overpressure control sensor</td></tr>
<tr><td colspan="2">Engine calculator (module)</td><td>Air intake system</td></tr>
<tr><td colspan="2">Atmospheric pressure sensor</td><td>Oil vapor recirculation</td></tr>
<tr><td colspan="2">Turbocharger overpressure control sensor</td><td>Cooler for supercharged air</td></tr>
<tr><td colspan="2">Intake air pressure sensor</td><td>Knock sensor</td></tr>
<tr><td colspan="2">Intake air pressure sensor</td><td>Fuel quality</td></tr>
<tr><td colspan="2">HP Pump</td><td rowspan="3"></td></tr>
<tr><td colspan="2">Exhaust system</td></tr>
<tr><td colspan="2">Compression pressure</td></tr>
</table>

Source: own study based on available data, technical documentation and diagnostics during the study carried out in 2017.

Table 6. List of identified parameters for DTC: P0087 for selected repairs

Symptoms / Repair	Unit	Repair number											
		2	3	4	6	9	10	11	13	15	21	23	25
The nature of the fault	1 − fixed, 0 − sporadic	0	1	1	1	1	0	0	1	1	1	0	0
The state of enrichment regulation	1 – closed loop, 0 – open loop	1	1	1	1	1	1	1	1	1	0	1	1
The calculated value of the load (filling)	%	100	23,92	27,06	14,12	59,22	28,63	32,55	31.37	34,12	45,88	30.59	23,92
Enrichment correction fast (row 1)	%	4	1	9	-3	32	20	15	26	29	28	32	35
Free enrichment correction (row 1)	%	53	30	28	28	45	29	30	24	38	28	21	22
Pressure in the intake manifold	mbar	1620	500	460	350	890	520	590	570	600	950	560	450
Engine speed	rpm	1925	1882	704	1483	713	760	997	807	819	1567	784	716
Vehicle speed	km/h	80	64	0	4	0	12	8	0	0	38	0	0
Drive for the accelerator pedal sensor 1	mV	2730	1010	400	400	400	410	950	400	390	2120	400	400
Accelerator pedal voltage 2	mV	1340	490	200	200	200	200	470	200	190	1060	200	200
Engine operation	1 – during the operation 2 – stop	1	1	1	1	1	1	1	1	1	1	1	1
Battery voltage	V	14,2	14,2	14,7	14,6	14,3	12,8	14	13,9	14,4	14,4	14,5	13,7
Engine operation (gear)	1 – gear engaged, 0 – neutral	1	1	0	0	0	0	1	0	0	1	1	0
Measured filling	%	142	33	27	20	63	30	34	33	36	66	24	24
The set intake pressure	mbar	1550	560	480	240	770	530	710	550	600	960	410	410
Gear shift status	1 – gear engaged, 0 – neutral	1	1	0	0	0	1	1	0	0	1	0	0

Source: own study based on available data, technical documentation and diagnostics during the study carried out in 2017.

In turn, table 7 presents the range of identified errors accompanying the P0087 error for 12 selected repairs in model D for algorithm 1 (see: Tab. 5).

According to the error characteristics, it should be emphasized that the P0087 code identified for the state in which the pressure measured in the injection manifold is lower than the set value. It is noteworthy that in the read parameters of the P0087 error, no additional parameters regarding the pressure measured in the injection manifold were recorded in the engine computer. The pressure value is identified in the errors accompanying the P0087 code. This means that the P1336, P1337, P1338, P1339 and P1340 errors, identified with the state of ignition failure, when identifying and recording to the engine computer contain all parameters of the P0087 error. Additional parameters have been characterized in tab. 8.

Table 7. List of errors associated with the P0087 error

Repair / Error code	P0087	P1336	P1337	P1338	P1339	P1340	P0172
R2	X	X		X			
R3	X	X	X	X	X	X	
R4	X	X				X	
R6	X						X
R9	X						
R10	X						
R11	X						
R13	X						
R15	X						
R21	X					X	
R23	X						
R25	X	X	X	X			

Source: own study based on the study carried out in 2017.

Table 8. Value comparison for selected repairs

Symptoms / Repair R	R2	R3	R4	R21
Mileage [km]	49372	56681	22420	88937
The setpoint of the inlet valve phase position	-25	-15	36	-2
Set value of enrichment	1.067	1.000	1.000	1.000
Coefficient of correlation of the composition of the mixture at the entrance [%]	0	13	-1	-2
Position of the intake camshaft phase shifter	-26	-15	30	-1
Adaptation of the crankshaft target during emptying (1-made, 2-unfinished)	1	1	1	1
Intake pressure measured [mbar]	630	1520	490	960
Filled up [%]	38	134	29	75
The temperature of the intake air [^{0}C]	22	11	23	14
The pressure set point in the petrol manifold [bar]	65	107	51	112
The pressure in the gasoline collector [bar]	65	11	13	7
Fuel level [l]	57	10	26	23

Source: own study based on the study carried out in 2017.

Repair 3 can be considered an interesting case, in which as the only one of the tested repairs you can observe a phenomenon other than in the others regarding the order of error identification in the car's computer. This applies to errors: P1336, P1337, P1338, P1339 and P1340. during the identification of which, in addition to the parameter values described above, the mileage of the vehicle is recorded during the identification (Tab. 9).

Table 9. List of parameter values for a selected repair group by faults

Fault code / Parameter	Intake manifold pressure [mbar]	Engine speed [rpm]	Vehicle speed [km]	Set intake pressure [mbar]	The pressure set point in the petrol manifold [bar]	The pressure in the gasoline collector [bar]
P1337	760	2304	35	730	119	11
P1338	790	1746	26	780	85	6
P1340	790	1746	26	780	85	6
P1336	760	2304	35	730	107	11
P1339	760	2304	35	730	107	11

Source: own study based on the study carried out in 2017.

In other cases, the parameter data for the errors indicated above were identical. This means that the errors were recorded at the same time.

The analysis of the correlation of parameters in the analysed repairs for the P0087 error stated very strong positive correlations (for $p < 0.05$). These were the following variables:

- intake manifold pressure and calculated load value (filling) (0.9842),
- measured filling and calculated load value (filling) (0.9759),
- set intake pressure and calculated load value (filling) (0.9481),
- slow enrichment correction (row 1) and calculated load value (filling) (0.8444),
- accelerator pedal sensor voltage 1 and intake manifold pressure (0.8507),
- accelerator pedal sensor voltage 1 and vehicle speed (0.85),
- accelerator pedal sensor 2 voltage and intake manifold pressure (0.8490), accelerator pedal 2 sensor voltage and vehicle speed (0.8439),
- measured filling and slow enrichment correction (row 1) (0.8249),

Then, an attempt was made to list the classified symptoms of client reports in order to confirm the possibility of assessing the choice of the inference algorithm in the diagnosis or fault process depending on the type and number of symptoms reported by users of the *D model* (tab. 10). In addition, the *Mileage* variable was added to table 10 in order to evaluate the correlation between the number of errors and the mileage. Next, a correlation analysis of the studied variables was performed for both algorithms of conduct 1 and 2.

Table 10. List of studied variables, divided into the type of inference algorithm used in the process of diagnosing HP pumps

Algori	var1*	var2*	var3*	var4*	var5*	var6*
1	60096	1	1	0	2	1
1	51345	1	0	0	1	1
1	37123	0	0	1	1	2
1	53496	0	0	1	1	2
1	28542	1	0	0	1	2
1	89120	1	0	0	1	2
2	11518	1	1	0	2	3
1	31652	0	1	0	1	3
1	22441	1	0	0	1	3
2	45382	0	1	0	1	3
1	53691	1	1	0	2	3
2	32646	1	1	0	2	4
2	7279	1	0	1	2	4
2	18932	1	0	0	1	4
2	23786	0	0	1	1	5
1	59471	1	1	1	3	5
1	66711	1	0	0	1	6
2	26989	1	0	0	1	6
1	28406	1	0	0	1	6
1	56686	1	1	0	2	8

*Variables in the table: var1 - mileage, var2 - autodiagnostics, var3 - power, var4 - vibration, var5 - total number of symptoms and var6 - Total number of fault codes.
Source: own study based on the study carried out in 2017

Tab. 11 presents the results of correlation analysis for previously indicated variables. These were *Mileage* and previously characterized symptoms of *self-diagnostics*, *power* and *vibration* and the accumulated number of symptoms present for each of the tested repair – *the total number of symptoms*.

Table 11. Analysis of the correlation of variables ($p<0.05$) characterized in tab. 10

Variable	var1*	var2*	var3*	var4*	var5*	var6*
var1	1.00	0.06	0.15	-0.11	0.08	-0.11
var2	0.06	1.00	0.00	-0.47	0.40	0.21
var3	0.15	0.00	1.00	-0.24	0.66	0.04
var4	-0.12	-0.47	-0.24	1.00	0.20	-0.02
var5	0.08	0.40	0.66	0.20	1.00	0.18
Var6	-0.11	0.21	0.045	-0.02	0.18	1.00

*Variables in the table: var1 - mileage, var2 - autodiagnostics, var3 - power, var4 - vibration, var5 - total number of symptoms and var6 - Total number of fault codes.

Source: own study using the Statistica 13.1 program.

Regardless of the repair algorithm, in the examined group of 20 units it was confirmed that only in 5 cases there were reports in which no self-diagnosis indicator was found in the set of indicators in the symptoms. It is noteworthy that in all five repairs, the lack of control was accompanied by one symptom, it was power or vibration. In addition, it was verified whether in the examined group the number of parameters increases with the increase of the mileage and age from the date of the beginning of the guarantee. Negative correlation between autodiagnostics and vibration.

5. SUMMARY

In the course of analyses and results obtained, it was found that there are no grounds to reject the main thesis formulated in the introduction. This means that the methodology for diagnosing HP pumps on the example of the EP6CDT engine requires a combination of computer diagnosis method and control of mechanical parameters. These were the assessment of the pump selector condition and compensator spring length, as well as high and low fuel pressure measurements. At this point, it should be emphasized that in the reconstructed diagnosis process, mechanical control was initiated by a diagnostic test (reading error codes from the engine computer). The reason for both interventions may be reports of users describing the nature of the failure. They were classified according to three symptoms: self-diagnostics, lack of power and vibrations.

As a result of the completed empirical proceedings, three generalizing conclusions can be formulated:

- First, by attempting to classify the stages of diagnosis and replacing the high pressure pump on the example of the EP6CDT engine, four successive stages can be distinguished. These were: the first stage – identification of the fault, second – diagnosis and verification, third – repairs and fourth, the last one, quality control of the intervention.
- The factors determining the correct diagnosis of the HP pump in the EP6CDT engines. The following were qualified: precise and comprehensible technical documentation, training of employees receiving service station customers and employees, correctly updated diagnostic tools and equipment, implementation of the diagnosis and verification process in accordance with available documentation.
- The last conclusion of the observation. From the perspective of procedures at authorized pump service stations, which as a result of verification were not allowed for further use are replaced with new ones. HP pumps are not regenerated.

The implementation of the objectives in this work initiated further areas of research. In order to confirm the conclusions drawn for confirmed empirical facts, an attempt should be made to analyse the failure of all elements of the fuel system. More precisely, a broader analysis of diagnostic parameters could provide new knowledge in the construction, diagnosis and improvement of low and high fuel pressure systems in SI engines. In addition, the identified reconstruction of the diagnosis process and correlation analysis of the variable parameter of the HP and LP system could be used to attempt to design the concept of a diagnostic system to solve the nature of defect described in the article.

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Piotr SLIŻ, Ph.D.– assistant professor at the Faculty of Management at the University of Gdańsk. His current research interests are focused on the use of information technologies in car diagnostics and on the environmental assessment of the life cycle as support for the sustainable development of motor vehicles with different types of drives.