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Analysis of the fuel dose correction change trend in the diesel engine

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Abstract

Abstract: The article contains a functional analysis of the diesel engine ECU controller in terms of estimating the fuel dose correction signal. The reasons for introducing fuel dose correction for injectors in the area of limit values were analyzed, indicating the need for the diesel engine diagnostic process according to OBDII procedures in terms of changes in this parameter during engine operation. It is possible to use the engine ECU controller to implement extended functional diagnostic procedures in the scope of controlling the increase in the fuel dose correction value in a continuous system after implementing the supplemented software. Observing the trend of fuel dose correction variability will determine in advance the risk of an error code and MIL indicator light for the diesel engine power supply system.

Keywords: diesel engine, fuel dose, Common Rail system, OBDII diagnostics

1. Introduction

The development of fuel production technology with the use of FAME (Fatty Acid Methyl Esters) biocomponents requires specialist research that allows for the identification of quality and operational problems of the fuel equipment of Diesel engines, indicating the possibilities of their solution (Caprotti et al, 2005; CEC/TC 19 WG24, 2011). One of the main quality parameters closely related to the structural and group composition of fuels intended for diesel fuel is the tendency to form PM (Particulate Matter) deposits. Important properties of the fuel in this aspect are: high viscosity, low volatility, olefin content, autocatalytic breakdown of fatty esters with the participation of metal ions (Chapman, 2010). The deposits formed in this way can cause a limitation of the throughput of multi--hole sprayers used in injectors of the electronically controlled fuel injection process HPCRS (High Pressure Common Rail System) (Cieślikowski, Jakóbiec, 2017). The results of scientific research indicate the intensification of corrosion processes of the fuel equipment of Diesel engines. The gradual growth of PM layers also leads to the loss of the ability to properly atomize the fuel in the engine chamber, blocking the position of the exhaust gas guide vanes of the VTG compressor and the exhaust gas flow channels in the DPF (Diesel Particulate Filter) and EGR (Exhaust Gas Recirculation) systems (Mazuruk, 2013).

The effects of these processes result in the occurrence of engine failure states, related to the recording of error codes in the controller, the MIL indicator light signaling and the transition to the substitute engine operating characteristics. The complex nature of the error code recording requires a multi--aspect diagnostic reasoning process. A thorough analysis of the read error codes and the progressive correction of the injector dosage together with the recording of the engine load status according to the “freeze frame” reading as well as the characteristics of the injector coil supply system against the background of the fuel pressure recording – allows determining the cause of the fault (Greuter, Zima, 2016; Dernotte et al, 2012). The tests performed indicated the need for periodic control of the fuel dose correction increment value in the HPCRS system, before the generation of error codes and the MIL indicator light signaling, in order to extend the period of failure-free operation of the diesel engine supply system. In this case, it is necessary to extend the scope of diagnostic reasoning regarding the configuration of the fuel injection dose in the HPCRS system, despite the lack of error codes indicating a system failure. Representative parameters of the system were checked, mainly the correction doses of individual injectors of the 4-cylinder engine, in order to assess their correct operation.

2. Object of diagnostic tests in the OBDII system

An important aspect of a comprehensive diagnostic test of a diesel engine is the control of the “Fuel Trim” parameter (periodic fuel dosing), despite the fact that the ECU (Engine Control Unit or ECM – Engine Control Module) does not generate any HPCRS system fault codes (Quigley et al, 2009). Proper analysis of parameters illustrating the injector dosing process according to OBDII data (On--Board Diagnostic level 2) can be a valuable diagnostic tool for the fuel injection control system and its operation. In this case, it is necessary to extend the scope of diagnostic reasoning to the issues of correct fuel injection in the HPCRS system before an error occurs indicating a system fault. In order to demonstrate the need to extend the diagnostic process, a series of measurements was performed showing the variability of injector dosing of a 4-cylinder engine as a function of operating time with a record of the vehicle’s operating mileage. Representative parameters of the system were checked, mainly the correction doses of individual injectors in order to assess the degree of operational wear. The ECU engine controller configures the optimal stoichiometric composition

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of the fuel dose, i.e. the share of air mass in relation to the fuel mass, which determines the process of complete and correct combustion. Properly corrected fuel dosage (fuel trim) is intended to compensate for differences in uneven operation of the engine cylinders – resulting mainly from the conditions and time of engine operation.

There are two fuel dose corrections for Petrol engine: STFT – Short Term Fuel Trim (STFT1 and STFT2), which is an immediate reaction of the ECU controller on the scale of the current load state, responding to the modulation of the O2 sensor signal (Olszowski, 209). The value of the short-term fuel dose is not stored in the Keep Alive Memory (KAM), while the long-term fuel dose correction LTFT – Long Term Fuel Trim (LTFT1 and LTFT2) is the result of repeat tests of the ECU controller in a closed loop of checks. The result of these checks is the determination of the dose correction stored in the KAM memory while maintaining access to STFT (Osipowicz, Stoeck, 2013a,b; Kędzia, 2009). Unlike Petrol engine engines, the introduction of adaptive fuel injection correction in the Diesel engine occurs only during idle speed, ensuring uniform torque output by individual cylinders. The ECU controller recognizes the phenomena of torque pulsation and differences in the angular acceleration of the engine shaft between the work of subsequent cylinders, estimating the fuel dose correction signal for the injectors (Merker et al, 2012). The sum of all corrections should approach 0 and is calculated according to the rule:

- + mg/stroke – lower torque – increase the fuel dose
- – mg/stroke – higher torque – decrease the fuel dose.

The scope of introducing fuel dose correction is limited by the course of the correct fuel combustion process, which determines the emission of toxic exhaust components according to the applicable standards. If the correction exceeds the value of +/–1.5 to 2.5 mg/cycle for most electromagnetic injectors and 0.8 mg/cycle for piezoelectric injectors – then the MIL indicator light is signaled and the error code is recorded (Ignaciuk, Gil, 2014). Diesel engine manufacturers therefore provide different values of correction doses, starting from 1–2 mg/cycle to 4 mg/cycle. The practices of repair shops indicate that an injector with a fuel dose correction above 4 mg/cycle is damaged. In the case of a negative correction of the injected fuel dose, a configuration error of the electrical impulse sent to the injector by the ECU controller is possible, which causes a delay in the injector opening time. Usually, however, a negative correction results from the effect of the need to equalize the torque of a multi-cylinder engine due to the uneven wear of the components responsible for the efficiency of the individual cylinders. It should be noted that first the correction specifies the injector opening time and then the fuel dose.

Reading the error code is the first stage of the diagnostic process, which should be extended by the analysis of reading "frozen frames", i.e. important engine operating parameters at the time of the error. The most common errors caused by fuel trims are: P0170: fuel trim bank 1, P0171: system too lean (bank 1), P0172: system too rich (bank 1), P0173: fuel trim bank 2, P0174: system too lean (bank 2), P0175: system too rich (bank 2). Frequently occurring error codes caused by injector dysfunction have a short designation according to ISO codes and factory data written as follows: P01**, P11** (fuel composition control system), PO2**, P12** (fuel supply system (injectors)), PO3**, P13** (ignition system), where ** indicates the location of the component or element of the system showing a damaged condition. Approved diagnostic testers facilitate the process of detecting engine damage resulting from the occurrence of an error code according to the recorded procedures defined and extended by the engine manufacturer. The fuel dose correction in the Diesel engine occurs only at idle speed (up to approx. 1100–1300 rpm), while for higher engine speeds the correction is 0 and the fuel is supplied according to the current dosing map. An example of the fuel dose correction value determined by the actual opening time of the HPCRS injector is presented in Table 1.

Table 1. Example of fuel dose correction of the HPCRS injector of the Mercedes w211 2.7 cdi engine. Source: ESI[tronic] Bosch information materials

Rotation speed and load	Injector opening time according to basic injection map wtrysku:	Short-term correction factor value	Actual injector opening time
850–1150 rpm; partial load	2 ms	0,3 ms	2,3 ms
	2,8 ms	0,3 ms	3,1 ms

3. Functional analysis of the fuel dose correction of the Diesel engine in the OBDII system

An important aspect of the OBDII diagnostic process is obtaining diagnostic information regarding the mass or volume value of the additional increase in the fuel dose introduced by the ECU controller for individual cylinders per one working cycle using a dedicated tester. The development of a set of test data for the needs of the analysis of the research process for M9R engines code: 802 Turbo Diesel 1995cm^3 Common Rail, for a vehicle with a mileage of 147,400 km was carried out using the Sody CAN-CLIP service diagnostic equipment with current Renault software, equipped with a diagnostic probe and an interface with an OBD II connector – ASO service level, software with online access through the Authorized Service of the brand (Fig. 1).

Fig. 1. CAN-CLIP 213 Probe Scanner, 32bit, 2GB RAM, 73737 head

An example of a record of the progressive correction of the fuel dose during the operation of the tested engine, at which the ECU controller did not generate an error and the MIL indicator light did not flash, is shown in Fig. 2. The measurement performed showed a large variation in the injector correction doses, which, however, does not directly indicate a failure state of their operation. The high value of the fuel dose correction for cylinder 3 is worth noting. The confirmation of the progressive correction state of the fuel dose for cylinder no. 3 during the engine operation is the earlier record of the y_{no} dose correction mg/cycle according to Fig. 3. The value of such a high correction is not indifferent for the VTG compressor and is undoubtedly one of the reasons for blocking the mechanism positioning the exhaust gas guide vanes (Stępień 2013, Cieślikowski 2011). The values of the fuel dose difference for individual cylinders for the vehicle mileage of 86,000 km are shown in Fig. 3, while the initial state of the dose correction difference is shown in Table 2.

Fig. 2. Example of dose correction [mg/cycle] for injectors (1–4), 5 – deviation of the injector supply pressure value [bar] for the M9R engine code: 802 Turbo Diesel 1995 cm^3 Common Rail. Source: Own study

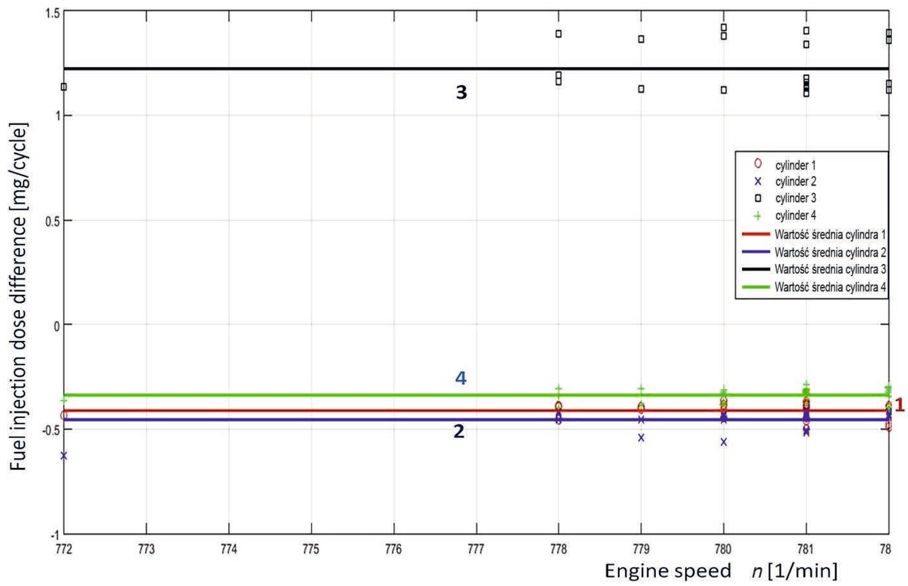

Fig. 3. Fuel correction dose difference values for injectors (1–4), for M9R engine code: 802 Turbo Diesel 1995 cm³ Common Rail for a mileage of 86,000 km. Source: Own study

Table 2. Average values of the fuel dose difference for individual cylinders. Source Own study

	Mean value [mg/stroke]	Standard deviation [mg/stroke]
Cylinder 1	−0,4218	0,0396
Cylinder 2	−0,4653	0,0536
Cylinder 3	1,2346	0,1301
Cylinder 4	−0,3457	0,0365

The measurements carried out with the EDIA-5 analyser (Fig. 4) enabled the recording of signals controlling the opening of the injectors and the time analysis of the amplitudes and the course of the increase in the high pressure value, indicating the progressive destruction of injector No. 3 as the main cause of the engine failure.

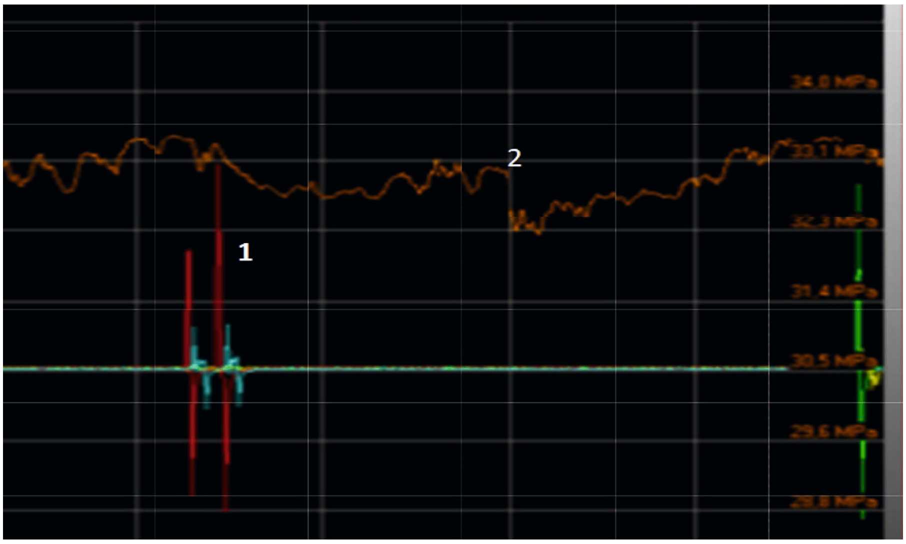

Fig. 4. Current characteristics of the injector coils (1) and the pressure in the "fuel rail" (2). Source: Own study

The recorded characteristics show the state of maintaining high pressure for an extended period of time for the injector for the 3rd cylinder, which suggests the possibility of coking of the multi-hole nozzle.

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4. Estimation of the trend of fuel dose correction changes using a regression model

A regression model of the type: diagnostic signal parameter as a function of the diagnostic parameter measure of the M9R engine code: 802 Turbo Diesel 1995 cm^3 CommonRail was developed. The tested car engine with a mileage of 147,400 km was subjected to full diagnostics along with an assessment of the operating parameters of the components according to the controller numbers and the functional dependency diagram on the CAN bus (Fig. 5).

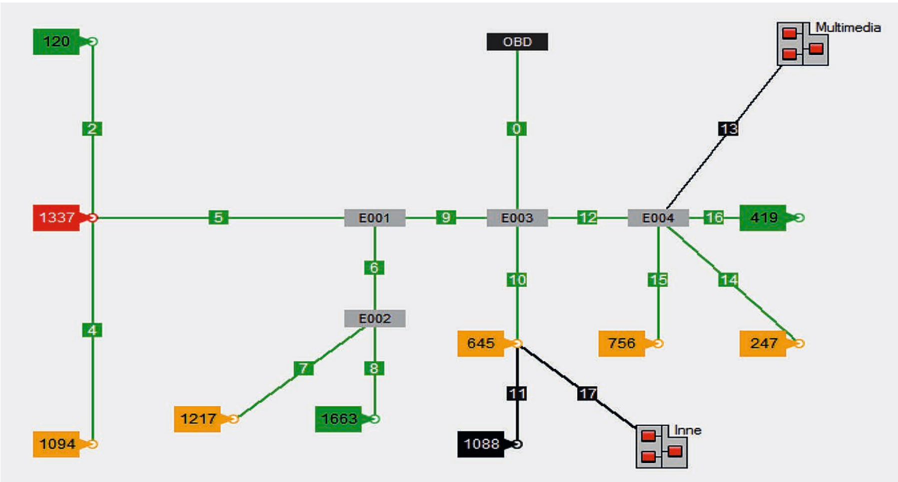

Fig. 5. Functional dependency diagram of the ECU engine controller with other controllers on the CAN bus according to the controller code numbers: CAN-CLIP 213 scanner. Source: Own study

Preparation of the engine for the diagnostic process was recorded according to the subsequent diagnostic stages of the CAN-CLIP 213 Probe Scanner – selected example Fig.6.

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1	MOMENT OBR. SILNIKA	26	Nm
2	PRĘDKOŚĆ OBR. SILNIKA	900	obr/min
3	TEMPERATURA PŁYNU	67	°C
4	NAPIĘCIE ZASILANIA KALKULATORA	14.76	V
5	PRĘDKOŚĆ SAMOCHODU	0	km/h
6	CIŚNIENIE ATMOSFERYCZNE	990	mbar
7	WYDATEK PALIWA	6.9	mg/cp
8	WYDATEK UKŁADU WYDECHOWEGO	69.5	m3/h

Fig. 6. Selected fragment of the engine preparation test for testing according to the recording of parameters with the CAN-CLIP 213 scanner. Designations: 1 – Engine torque [Nm], 2 – Engine speed [1/min], 3 – Engine coolant temperature [0C], 4 – Scanner supply voltage [v], 5 – Vehicle speed [km/h], 6 – Atmospheric pressure [mbar], 7 – Injected fuel dose [mg/cycle, 8 – Volume output of the exhaust system [m^3/h]. Source: Own study

The trend of the increase in the correction dose of each injector of the 4-cylinder engine was analyzed, determining the exponent defining the nature of changes in the technical condition of the object. The engine operation measurement interval (Fig. 7) was related to the measured limit values of the injector correction dose divided every 1500 km of engine operation, additionally analyzing the trend of the operation curve. The limit measure of vehicle operation is determined by obtaining the limit value of the fuel dose correction by one of the engine injectors. The range of correct injector operation wear is therefore determined by an additional engine operation measurement interval T_3.

The possibility of forecasting the technical condition of the injector based on the intensity of the change of the diagnostic parameter for the increment of the dose correction until the limit value y_{nk} is reached and the MIL indicator light is signaled is presented:

$$y_n(v) = y_{no} + \Delta y_n * v^{\alpha} \tag{1}$$

where: $y_n(v)$ – value of the diagnostic parameter, i.e. fuel dose correction; y_{n0} – initial value of the diagnostic parameter; Δy_n – intensity of the parameter change in the scale of engine operation time intervals; v – measure of operation – number of months of engine operation; α – exponent of the power defining the nature of the change of the dose parameter in the measure intervals of operation.

The resource reserve of the object can be written as:

$$v_n = v\left[\left(\frac{y_{nk}}{y_n(v)}\right)^{\frac{1}{\alpha}} - 1\right] \quad (2)$$

where: V_z – resource reserve of the object; V – interval of the number of correction dose control cycles in a monthly division of the operating time; y_{nk} – limit value of the diagnostic parameter of the correction dose in relation to y_{n0}; $y_n(v)$ – variable value of the diagnostic parameter of the correction dose.

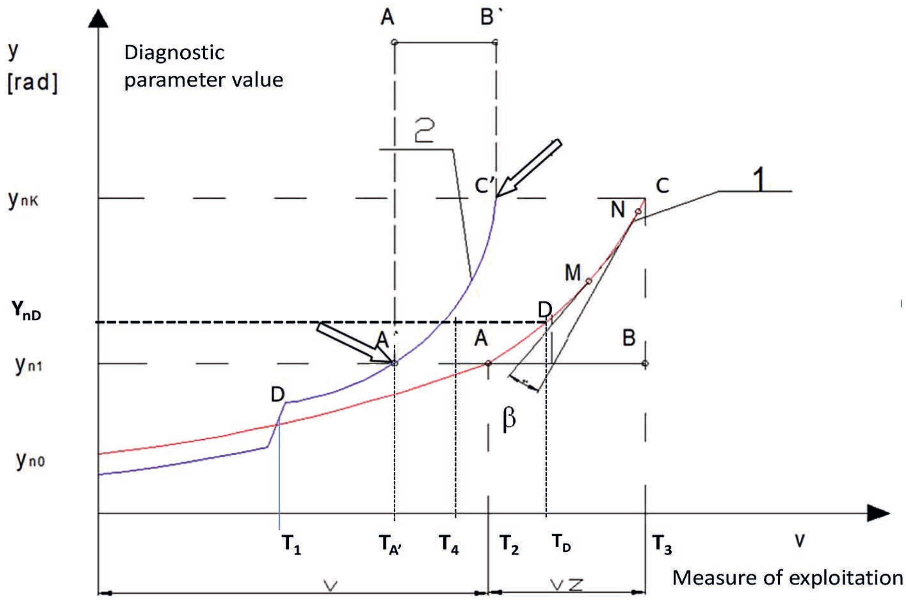

Fig. 7. Characteristics of the changes in the correction dose as a function of the engine operating parameter. 1 – the process of uniform increase in the correction dose for the 2nd cylinder injector, 2 – accelerated increase in the correction dose of the 3rd cylinder ended with exceeding the limit value to y_{nk}. Source: Own study

The engine functional diagnostics process in this case consists in determining the trend of the operating curve as a result of recording the course of changes in the dose correction parameter in the time intervals of performing the diagnostic control. Determining the dose correction limit state parameter based on the ordinate value y_{nk} is burdened with a significant error resulting from both the individual feature of the object y_{n0} and the possibility of increased wear of the HPCRS injector. The process of gradual increase of the y_n value in the V_z interval is possible only in the case of uniform operational wear of the injector. The analysis is subjected to the mean curvature $k(MN)$ of the MN arc on the characteristic according to Fig. 7 as the absolute value of the arc measure of the angle β contained between the tangents in M and N to the length $|MN|$ as:

$$k(MN) = \frac{|\beta|}{|MN|} \quad (3)$$

Obtaining signal continuity provides a basis for recording the trend of the increase of the $y_n(V)$ parameter in the range of the engine operating parameter V_i. Thus, the analysis of the $k(MN)$ curvature in the control ranges determined by the arc curvature constitutes the process of estimating the functional diagnostic parameter for fuel dose correction. By narrowing the control range, i.e. when point N tends to point M, we determine the location of the center of the MN arc curvature. The curvature in the described range is equal to the inverse of the radius of curvature R_M. If the curve equation is written in the form $y=f(x)$ and the function $f(x)$ has a second derivative, the radius of curvature in the $M(x,y)$ range of this curve is expressed by the relationship:

$$R_M = \frac{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}}{\left|\frac{d^2y}{dx^2}\right|}; \quad \frac{d^2y}{dx^2} \neq 0 \tag{4}$$

If the function $y=f(x)$ has an extremum at the point $x=x_0$, then $\left(\frac{dy}{dx}\right)_{x_0}=0$ and therefore the curvature k_M equals the absolute value of the second derivative at this point:

$$k_M = \left|\left(\frac{d^2y}{dx^2}\right)_{xo,yo}\right| \tag{5}$$

The curvature k_M at point M is the limit of the curvature of the mean arc MN of this curve when point N tends to point M in accordance with the notation:

$$k_M = \lim_{M \to N} k(MN) \tag{6}$$

Therefore, the diagnostic signal estimation regarding the HCPR system injector dysfunction comes down to comparing the course of the relative dose correction value increase before the limit value of the operating measure parameter y_{nk} is reached. It will then be possible to undertake an intervention to repair or replace the injector before the error code is recorded, the MIL indicator light turns on and the engine ECU controller switches to the substitute characteristic of the engine failure state.

The obtained values of subsequent engine correction dose checks in intervals of 1500 km of operation for the range of parameter variability between T_1 and T_3 constitute sets of points described by the courses of curves 1 and 2. It is necessary to perform numerical analysis as spline interpolation, in which the interpolant is a type of fragmentary polynomial called a spline. In practice, it is difficult to match a single high-degree polynomial to all values of the set of variables, which results from further operation of the engine with a damaged injector. A useful feature of spline interpolation is a small interpolation error even when using low-degree polynomials for the spline (Burden, 2015). In the analyzed case, the sets of measurement points of the correction doses for each injector create a sequence of nodes. Therefore, a cubic polynomial $q_i(x)=y$ will be described between each successive pair of nodes $n+1$ and $(x_{i-1}, y_{i-1})i$ where $i=1,2,3\ldots n$. Polynomials n will be created starting from ending with the last. Any curve will be determined according to the notation:

$$K = \frac{y''}{(1+y'^2)^{3/2}} \tag{7}$$

Each subsequent polynomial for the injectors of a multi-cylinder engine must refer to a comparison of the values of the same y for subsequent dose correction values for individual injectors. The first and second derivatives satisfy the condition when connecting nodes:

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$$\begin{gathered} q_i(x_i) = q_{i+1}(x_i) = y_i \\ q_i'(x_i) = q_{i+1}'(x_i) \\ q_i''(x_i) = q_{i+1}''(x_i) \\ 1 \le i \le n-1 \end{gathered} \tag{8}$$

This condition can be achieved when a 3rd degree polynomial is used.

To compute derivatives (including higher-order ones), we use the so-called finite difference method. The evaluation of the trend of the change in the diagnostic parameter is consistent with the evaluation of the changes in the curvature related to the nature of the curve. In the case of a strong change in the nature of the curvature growth, i.e. a rapid increase in the ordinate y_n in the ranges of the operating parameter, we can more accurately determine the condition of the object. In the case of accelerated wear of the assembly element (curve no. 2 in Fig. 7), the further course of the curve is characterized by a greater increase in the ordinates for the diagnostic control points than in the case of the course of curve no. 1 for uniform wear of injector no. 2. The ECU injection controller can analyze the injector dose correction parameters also in relation to the time of effective engine operation, eliminating, for example, the engine warm-up phases, which could contribute to the introduction of incorrect data.

Let us assume that we want to describe the polynomials for curves 1 and 2 (Fig. 7) between two subsequent measurements starting from the same value y_{n1} corresponding to the fuel dose correction of 0.4 mm³/cycle, to the value y_{nD} for the dose of 0.9 mm³/cycle on curves AC, $A'C'$ for the next measurement y_T at different engine operating times as: $(x_{TA'}, y_{n1})$, (x_{TA}, y_{nD}), $(x_{T2'}, y_{n1})$, (x_{TD}, y_{nD}).

The subsequent values of the fuel dose correction during further engine operation will determine the set $q_i(x)$ for curves 1 and 2 described for the y_{ni} values as: (x_0, y_0) to (x_n, y_n).

The analysis will be performed on the slope of the k curve connecting the next points k_0 to k_n according to the record for the adjacent measurement points:

$$q(x_n) = y_n \qquad q'(x_n) = k_n \qquad q' = \frac{dq}{dt}\frac{dt}{dx} = \frac{dq}{dt}\frac{1}{x_{i+1} - x_i} \tag{9}$$

$$\begin{gathered} q(x_i) = y_i \\ q(x_{i+1}) = y_{i+1} \\ q'(x_i) = k_i \\ q'(x_{i+1}) = k_{i+1} \end{gathered}$$

A significant increase in the fuel dose correction value indicates a significant fragment of the diagnostic parameter change marked in the time interval $t = 0$ and $t = 1$ as the first derivative: $q'(x_1) = k_1$ oraz $q'(x_2) = k_2$ determining the slope of the curvature in the observation time interval. Observation of the curvature variation trend to a satisfactory degree will indicate the risk of an error code and MIL warning light. The determined margin of vehicle operation measure V for the diagnosed object according to curve no. 1 cannot be referred to the course of wear according to curve no. 2 with the same value of parameter y_{n1}, because in this case the limit value of parameter y_{nk} for value C' in relation to C will be exceeded earlier. This is indicated by the different length of section AB in relation to AB' (Fig. 7) by the operation time interval increased by the value V_z for normal operating wear of injectors.

In the analyzed example, this increase amounted to 16 months as an extension of the vehicle's service life by 63,000 km, while the vehicle engine was working on the replaced injector no. 3. The existing state of disproportion in the growth of the fuel dose correction should be signaled by the need for vehicle service intervention before the state of the fuel dose correction limit value occurs. Additional repair intervention in the form of replacing the injector elements or ultrasonic cleaning of the nozzle holes and performing a test on the BOSCH EPS 815 or CRi-PC machine together with calibration and assigning a new data code to the injector, will effectively contribute to extending the engine's service life without the need to replace the malfunctioning injector earlier (Osipowicz, Stoeck 2013a,b).

There is therefore a need to modify the engine ECU controller software in the dynamic control module for the analysis of diagnostic parameters, which in the analyzed case directly refers to the comparative analysis of the corrections of the doses of diesel engine injectors. These modifications can only be implemented by engine manufacturers at the stage of engine testing on the dynamometer. Before this happens, it is justified to periodically check the injector correction doses as a supplement to the engine service diagnostics process using OBDII diagnostic methods. The fundamental diagnostic criterion therefore refers to distinguishing between the uniform and dynamic operating wear of the injector.

5. Conclusions

1. A priori determination of the limit value of the HPCRS system wear parameter ordinate may be a source of diagnostic errors and is the cause of too late detection of the threat of engine power system failure.
2. The limit value of the wear ordinate of a uniform nature does not correspond to the ordinate with a varied degree of component wear.
3. It is possible to use the engine ECU controller to implement functional diagnostic procedures of the HPCRS engine power lecture in the scope of controlling the increase in the fuel dose correction value in a continuous system after implementing the supplemented ECU controller software.
4. It is necessary to individually identify parameters for various HPCRS system designs in the scope of: symptom - diagnostic parameter value in engine operation time intervals.
5. Earlier diagnostic information regarding an approaching HPCRS system failure will enable undertaking repair intervention, eliminating premature replacement of system components, which will reduce the costs of vehicle operation and road interventions.

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