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Assessment of controlling effectiveness of a combustion engine's utility parameters in relation to ecological and utility criteria

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Abstract. Compression ignition engine is very often used as a power unit in any type of vehicles, as well as in stationary installations. This is mainly due to high efficiency of such engines and resulting low fuel consumption. There exists clear relation between the utility parameters of the engine and emission level of air pollutants. Obtainment of satisfactory relation between the utility parameters of the engine and the emissions level creates a difficult task, requiring great knowledge and experience. To support decision-making process, a method how to assess results of controlling of the utility parameters of compression ignition engine has been depicted in the presented study. It has been proposed how to perform multicriteria assessment in relation to the utility and ecological criteria. Within group of the ecological criteria, emission levels of individual harmful components of exhaust gases were taken as the partial criteria to the assessment. In turn, parameters such as value of mean indicating pressure, thermal efficiency, maximal temperature and pressure of the cycle were considered within group of the utility criteria. Within framework of the study it has been performed evaluation of a few sets of the utility parameters, obtained in course of numerical calculations of partial engine loads. The calculations have comprised resolving of minimization task of nitrogen oxides emissions with limitations imposed on the utility parameters and other harmful compounds of exhaust gases. The method of analytic hierarchy process was applied to accomplishment of the multicriteria assessment.

1. Introduction

In case of a piston-type combustion engine, substances causing pollution of the natural environment can be emitted from three sources: from crankcase, from fuel supply system, and from exhaust system [5]. The most crucial are emissions from the exhaust system, emitting products of incomplete combustion of liquid fuel. In the compression ignition engines (CI), in spite of supplied excess of air, combustion is incomplete, what can lead to generation in exhaust gases with substances containing carbon. In turn, presence of nitrogen oxide is an effect of secondary reactions in process of the combustion. Emission of nitrogen oxides mentioned here, being effect of combustion, is significantly connected with the utility parameters of the engine. An attempt was made in the study to determine minimal level of nitrogen oxide emission at assumed values of the utility parameters and emission levels of other components of exhaust gases.

2. Model of working cycle of the compression ignition engine

The phenomena occurring in the engine cylinder can be described by a set of differential equations and some algebraic relations [8]. We assumed that the vector of independent input parameters of the computational model of the working cycle has the following form:

$$\boldsymbol{X} = \left[n, B_0, \varphi_w, X_{EGR}\right]^T . \tag{1}$$

where: n - crankshaft rotational speed, B_0 - injected fuel mass, φ_w - injection advance angle, X_{EGR} - degree of exhaust gas recirculation.

The additional relations defining quantities appearing in the computational model are introduced by the following vector of model parameters:

$$\boldsymbol{E} = \left[\mu_d, \mu_w, \Delta\varphi_s, \varphi_z, \beta, e_1 ... e_8\right]^T . \tag{2}$$

where: $e_1 \dots e_8$- additional model constants, selected during calibration of the model.

Then, the semi-empirical single-zone model of the working cycle of the CI engine which enables calculation of the pressure, mass and temperature courses in the cylinder i.e. $m_c(\varphi)$, $p_c(\varphi)$, $T_c(\varphi)$ respectively, where φ is the crankshaft angle, can be written as [3]:

$$\frac{\mathrm{d}m_c}{\mathrm{d}\varphi} = \frac{\mathrm{d}m_d}{\mathrm{d}\varphi} - \frac{\mathrm{d}m_w}{\mathrm{d}\varphi} + \frac{\mathrm{d}m_f}{\mathrm{d}\varphi} \tag{3.1}$$

$$B_0 W \frac{\mathrm{d}y}{\mathrm{d}\varphi} + \frac{30}{\pi n} h_c A_h (T_s - T_c) + c_{pd} T_d \frac{\mathrm{d}m_d}{\mathrm{d}\varphi} = c_{vc} T_c \frac{\mathrm{d}m_c}{\mathrm{d}\varphi} + c_{vc} m_c \frac{\mathrm{d}T_c}{\mathrm{d}\varphi} + p_c \frac{\mathrm{d}V_c}{\mathrm{d}\varphi} + c_{pw} T_w \frac{\mathrm{d}m_w}{\mathrm{d}\varphi} \tag{3.2}$$

$$\frac{\mathrm{d}m_{d(w)}}{\mathrm{d}\varphi} = \frac{\pi n}{30} \mu_{d(w)} A_{d(w)} p_{d(c)} \left[\frac{2}{R_{d(c)} \cdot T_{d(c)}} \frac{k_{d(w)}}{k_{d(w)} - 1} \left(\beta_{d(w)}^{\frac{2}{k_{d(w)}}} - \beta_{d(w)}^{\frac{k_{d(w)}-1}{k_{d(w)}}} \right) \right]^{1/2} \tag{3.3}$$

$$p_c V_c = m_c R_c T_c \tag{3.4}$$

$$y = \beta \left[1 - \left(1 - \left(\frac{\varphi - \varphi_z}{\Delta\varphi_s} \right)^{e_1 \tau} \right)^{e_2} \right] + (1 - \beta) \left\{ 1 - \exp\left[e_3 \lambda \left(\frac{\varphi - \varphi_z}{\Delta\varphi_s} \right)^{e_4} \right] \right\} \tag{3.5}$$

$$h_c = e_5 V_c^{e_6} p_c^{e_7} T_c^{e_8} \cdot (\bar{s} + 1.4)^{0.8} \tag{3.6}$$

where: $\beta_d = p_c p_d^{-1} \le 1$, $k_d = c_{pd} c_{vd}^{-1}$, $\beta_w = p_w p_c^{-1} \le 1$, $k_w = c_{pc} c_{vc}^{-1}$, subscript c is used for parameters in the cylinder, d in the intake, and w in the exhaust manifold, A - valve flow area, A_h - heat transfer area, c_p - specific heat of the medium at constant pressure, c_v - specific heat of the medium at constant volume, h_c - heat transfer coefficient, m - mass of the medium, m_f - mass of the fuel, p - pressure, R - gas constant, $\bar{s}$ - mean piston speed, T - temperature, T_s - wall temperature, τ - ignition delay time, V_c - cylinder volume, W - fuel caloric value, y - fuel mass burning rate, λ - relative air/fuel ratio, φ- crank angle, φ_z - start of combustion, $\Delta\varphi_s$ - total combustion duration, μ_d - inlet valve discharge coefficient, μ_w - exhaust valve discharge coefficient.

In scope of estimation of harmful compounds emissions like carbon monoxide, hydrocarbons, nitrogen oxides and smoke, implemented model is supplemented by relevant dependencies of the form [4]:

$$F_i = f_i(\boldsymbol{X}) \tag{4}$$

where $i \in \{CO, HC, NO_x, D\}$; CO, HC i NOx were measured in ppm whereas smoke in FSN.

3. Subject of the study

Model of the working cycle presented in the previous chapter constitutes the tool enabling selection of adjusting parameters of the engine (fuel dose, injection advance angle, degree of exhaust gas recirculation) due to any objective function. Considerations performed in the present study comprise selected issue of assessment of the controlling efficiency through selection of adjusting parameters in relation to minimization task of nitrogen oxides emission from the CI engine. Model tests were performed for previously calibrated model of the working cycle of the engine, which main technical parameters are specified in table 1.

Table 1. Main technical parameters of the engine

Engine	Compression ignition, turbocharged, common rail system
Swept capacity	1.3 dm^3
Maximal power	55.2 kW / 4000 rpm
Maximal torque	190 Nm / 1500 rpm

As starting point to the considerations undertaken in this study were used results of the controlling obtained for some selected points of engine operation and presented within framework of the previous studies performed by the authors [6, 7], in which the objective function has taken form:

$$\overline{\Omega}_{NO_x}\left(\boldsymbol{X}\right)=C_{NO_x}^{F}F_{NO_x} \tag{5}$$

where: F_{NO_x} - emission of nitrogen oxides in the exhaust gases, $C_{NO_x}^{F}$ - coefficient defined with reference to emission of nitrogen oxides for factory settings of the engine, together with limitations relating to allowable emission levels of other harmful components of exhaust gases and changes in characteristic parameters of the working cycle. Increase in emissions of carbon monoxide, hydrocarbons and smokiness with 30%, 20% and 50% max respectively, with regard to values obtained for the factory settings, was allowed in discussed in this paper task of selection of the adjusting parameters. Moreover, it has been allowed reduction of thermal efficiency of the engine with 5% max, and increase of maximal pressure and maximal temperature of the cycle with 10%.

Objective of the presented study is multicriteria assessment of results obtained from the task in form as described in (5), which enables evaluation of controlling effectiveness of the adjusting parameters of compression ignition engine in ecological and utility aspects. These results will be analyzed for a few operational points of the engine, corresponding to selected conditions of partial engine loads, as shown in table 2.

Table 2. Points of engine operation, for which controlling effectiveness of the adjusting parameters was analyzed ($M_{\max}$ denotes maximal torque at a given rotational speed)

	P1	P2	P3	P4	P5	P6	P7	P8
Rotational speed [rpm]	2500	2500	2500	2500	3500	3500	3500	3500
Load	0.25 $M_{\max}$	0.50 $M_{\max}$	0.75 $M_{\max}$	0.90 $M_{\max}$	0.25 $M_{\max}$	0.50 $M_{\max}$	0.75 $M_{\max}$	0.90 $M_{\max}$

To perform the multicriteria assessment of controlling efficiency it has been implemented method of the analytic hierarchy process [9]. This method enables decomposition of the assessment issue against both cumulated categories, as well as factors being part of individual categories. Within framework of individual cumulated categories the following specific criteria were taken to the assessment:

a) ecological category (*EX*): emission of carbon monoxide F_{CO}, emission of hydrocarbons F_{HC}, emission of nitrogen oxides $F_{NOx,}$ and smokiness of exhaust gases F_D,
b) utility category (*UT*): mean indicating pressure p_i, thermal efficiency of the cycle η_c, maximal pressure in the cylinder p_{max} and maximal temperature in the cylinder T_{max}.

Results of the applied controlling, referenced to parameters comprising specific criteria of the assessment and juxtaposed in form of table 3 have constituted the basis to the analysis discussed in the present study.

Table 3. Percentage change of parameter being specific criterion of the assessment due to implementation of the controlling in relation to value of this parameter, recorded for the factory settings

Change of the parameter [%]	Points of engine operation							
	P1	P2	P3	P4	P5	P6	P7	P8
F_{CO}	30.0	23.8	30.0	18.7	29.8	22.1	3.9	1.3
F_{HC}	14.3	-8.3	-3.8	-3.0	-8.9	-5.1	-2.7	-3.2
F_{Nox}	-27.3	-30.6	-9.5	-9.6	-70.9	-20.6	-13.3	-15.6
F_D	37.4	50.0	44.9	50.0	49.5	50	50	50
p_i	4.8	-0.1	0	-0.1	0.1	-0.1	-0.1	-0.2
η_c	-4.7	-0.5	-0.3	-0.2	-0.5	-0.1	-0.2	-0.1
p_{max}	-2.3	-1.6	-0.4	-0.5	-3.2	-0.6	-0.6	-0.8
T_{max}	4.6	5.0	0.9	0.0	1.0	-5.2	-6.0	-3.0

General form of the hierarchic structure representing analysed in this study issue of assessment of the set with results from the selection task of the adjusting parameters has structure as shown in figure 1.

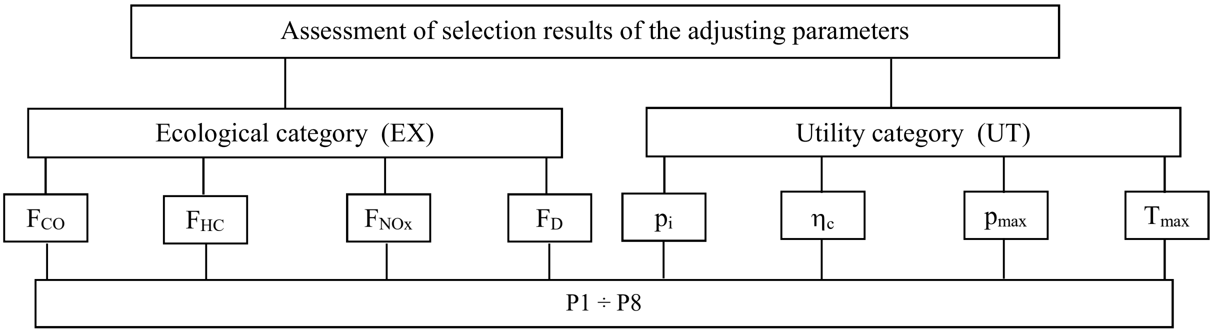

Figure 1. Decomposition scheme of the assessment task of selection results of the adjusting parameters.

Method of decomposition of analysed in this study issue of the assessment was presented in figure 1. It can be seen that controlling effectiveness for each from the operational points is analyzed separately because of each from factors constituting specific criterion of the assessment. In turn, elements from the higher level include the cumulated categories. Significance of individual specific factors, constituting a given cumulated category, is evaluated at this level. Final assessment is possible after evaluation of mutual significance level of analyzed cumulated categories. Pairwise comparison is the basis of performed relative assessment at all stages of the analysis. Classic Saaty scale was used to quantification of the relative assessments [9].

4. Assessment of controlling results with respect to individual specific criteria

Matrix of preferences is determined at the first stage in order to make assessment of the controlling effectiveness of each from analysed specific criteria. Assuming that for the specific criterion *k,* the $r_{ij}^{(k)}$ is the relative assessment of the controlling obtained for the operating point P_i, in comparison to that one obtained for the operating point P_j, created matrixes of preferences $\boldsymbol{R}^{(k)}$, $k = 1,..,8$ are the square matrixes in form:

$$\boldsymbol{R}^{(k)} = \begin{bmatrix} r_{1,1}^{(k)} & \cdots & r_{1,8}^{(k)} \\ \vdots & r_{i,j}^{(k)} & \vdots \\ r_{8,1}^{(k)} & \cdots & r_{8,8}^{(k)} \end{bmatrix} \tag{6}$$

In this study the values of $r_{ij}^{(k)}$ were obtained calculating quotients of the values presented in table 3, obtained for the operating points P_i and P_j respectively for the criterion *k*, and next rescaling linearly obtained result to range of values used on the Saaty scale. Next, it has been evaluated vectors of priorities representing assessment of the controlling effectiveness due to isolated specific criterion *k* by solving the equation:

$$\boldsymbol{R}^{(k)}\boldsymbol{W}^{(k)} = \lambda \boldsymbol{W}^{(k)} \tag{7}$$

where: λ - maximal eigenvalue of the matrix $\boldsymbol{R}^{(k)}$, $\boldsymbol{W}^{(k)} = \left[w_1^{(k)},..., w_8^{(k)}\right]^T$ and $\sum_i w_i^{(k)} = 1$.

Vectors of priorities were determined with use of the iterative method [10], assuming that allowable evaluation error of the vector component's value is not bigger than 10^{-5}. In figure 2 and 3 are presented results of the first stage assessment, illustrating values of the vector $\boldsymbol{W}^{(k)}$ for each specific criterion.

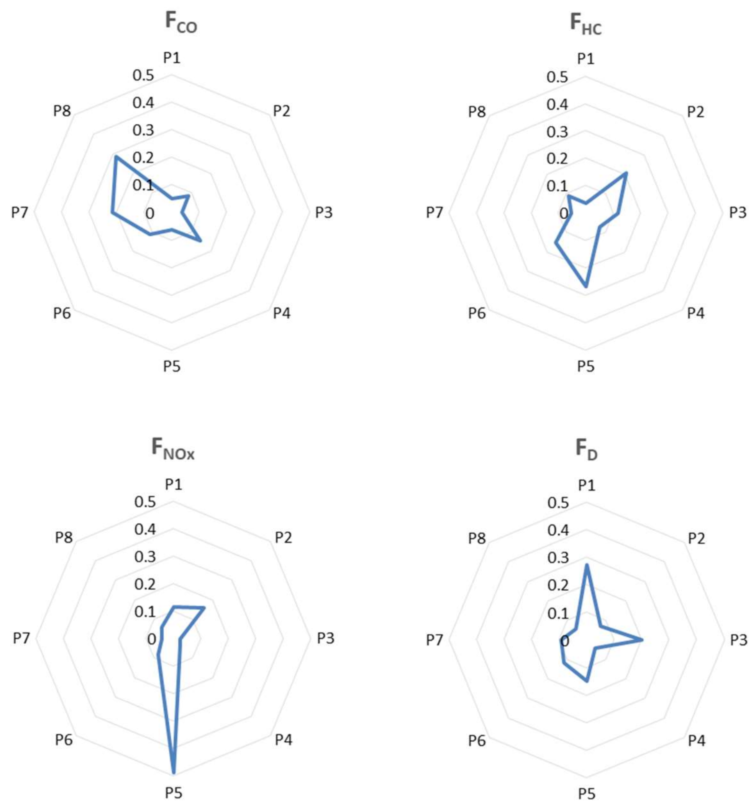

Figure 2. Graphical representation of values of the vector of priorities for the ecological criteria.

Figure 3. Graphical representation of values of the vector of priorities for the specific utility criteria.

In successive stage of the proceeding it has been determined vectors of relative assessments within scope of analysed cumulated categories.

5. Assessment of significance of the specific criteria

Investigating the cumulated category, which comprises the ecological properties, significance level of the emission of individual harmful components of exhaust gases was determined on the basis of the following presumptions:

– with reference to the objective function implemented during resolving of the selection task of the adjusting parameters, in the ecology context, the emission of nitrogen oxides was assumed as the most important criterion to assessment of the obtained results,

– smokiness of the exhaust gases was recognized as more significant factor than emission of hydrocarbons and carbon monoxide, due to greater harmfulness of the sooth, resulting from strong tendencies to binding of hydrocarbons generated in course of indirect processes, especially having ring structure [2],

– emission of hydrocarbons and emission of carbon monoxide are the issues of a similar significance for the analysed type of the engine, with a light indication on preference in area of restriction of hydrocarbons emission, because of lower tendency to oxidation.

Matrix of preference for the ecological criteria, obtained in result of pairwise comparisons has the following form:

$$\boldsymbol{M}_{EX} = \begin{bmatrix} 1 & r_{CO\leftrightarrow HC} & r_{CO\leftrightarrow NOx} & r_{CO\leftrightarrow D} \\ r_{HC\leftrightarrow CO} & 1 & r_{HC\leftrightarrow NOx} & r_{HC\leftrightarrow D} \\ r_{NOx\leftrightarrow CO} & r_{NOx\leftrightarrow HC} & 1 & r_{NOx\leftrightarrow D} \\ r_{D\leftrightarrow CO} & r_{D\leftrightarrow HC} & r_{D\leftrightarrow NOx} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/2 & 1/9 & 1/7 \\ 2 & 1 & 1/7 & 1/5 \\ 9 & 7 & 1 & 5 \\ 7 & 5 & 1/5 & 1 \end{bmatrix} \tag{8}$$

Vector of priorities calculated in the next step, representing in the assessment of the controlling efficiency the significance of emissions of individual harmful compounds of exhaust gases has form:

$\boldsymbol{EX} = [0.043;\ \ 0.070;\ \ 0.645;\ \ 0.242]^T$ for $ex_1 = F_{CO};\ \ ex_2 = F_{HC};\ \ ex_3 = F_{NO_x};\ \ ex_4 = F_D$

Next, considering cumulated category comprising the utility parameters, significance level of individual parameters analysed within framework this category has been determined on the basis of the following presumptions:

- limitation of maximal temperature was considered as more important than limitation of maximal pressure in the cylinder; because higher temperature of the cycle has important effect on durability of exhaust valves, on durability of supercharging system with turbocharger, durability of recirculation system of the exhaust gases, and on durability of after-treatment system of exhaust gases comprising catalytic converter and DPF [1],
- higher temperature of working medium in the cylinder promotes increased emission of nitrogen oxides.

The preference matrix obtained in result of pairwise comparisons of the utility parameters has form:

$$\boldsymbol{M}_{UT} = \begin{bmatrix} 1 & r_{p_i\leftrightarrow\eta_c} & r_{p_i\leftrightarrow p_{max}} & r_{p_i\leftrightarrow T_{max}} \\ r_{\eta_c\leftrightarrow p_i} & 1 & r_{\eta_c\leftrightarrow p_{max}} & r_{\eta_c\leftrightarrow T_{max}} \\ r_{p_{max}\leftrightarrow p_i} & r_{p_{max}\leftrightarrow\eta_c} & 1 & r_{p_{max}\leftrightarrow T_{max}} \\ r_{T_{max}\leftrightarrow p_i} & r_{T_{max}\leftrightarrow\eta_c} & r_{T_{max}\leftrightarrow p_{max}} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 7 & 5 & 5 \\ 1/7 & 1 & 3 & 2 \\ 1/5 & 1/3 & 1 & 1 \\ 1/5 & 1/2 & 1 & 1 \end{bmatrix} \tag{9}$$

what has enabled determination of the vector of priorities, representing significance of analysed utility parameters having form:

$\boldsymbol{UT} = [0.65;\ \ 0.17;\ \ 0.087;\ \ 0.093]^T$ for $ut_1 = p_i;\ \ ut_2 = \eta_c;\ \ ut_3 = p_{max};\ \ ut_4 = T_{max}$

6. Assessment of significance of the cumulated categories and result of the multicriteria assessment

To make final prioritization of the results obtained for individual points of engine operation because of overall effectiveness of the controlling, matrix of preferences related with individual cumulated categories should be determined in the first place, and next vector of priorities. Significance of the individual cumulated categories was determined, recognized the ecological criterion as slightly more significant than the utility criterion. It results from the environmental pollution by emission of harmful compounds of the exhaust gases and increased fleet of road-going vehicles.

Matrix of preferences obtained in result of the pairwise comparisons for the cumulated categories has form:

$$\boldsymbol{M}_1 = \begin{bmatrix} 1 & r_{EX\leftrightarrow UT} \\ r_{UT\leftrightarrow EX} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 4 \\ 1/4 & 1 \end{bmatrix} \tag{10}$$

Hence, calculated vector of priorities, representing significance of the cumulated categories has form:

$\boldsymbol{I} = [0.84;\ \ 0.16]^T$ for $i_1 = EX;\ \ i_2 = UT$.

In the last stage of the proceeding it has been determined vector of global priorities $\boldsymbol{G} = [g_1,...,g_8]^T$, individual components of this vector are calculated as:

$$g_i = i_1 \sum_{j=1}^{4} ex_j w_i^{(j)} + i_2 \sum_{j=1}^{4} ut_j w_i^{(4+j)} \tag{11}$$

Graphical presentation of evaluated values of the vector of global priorities ***G*,** and values of the local priorities, in relation to analysed cumulated categories, is shown in figure 4.

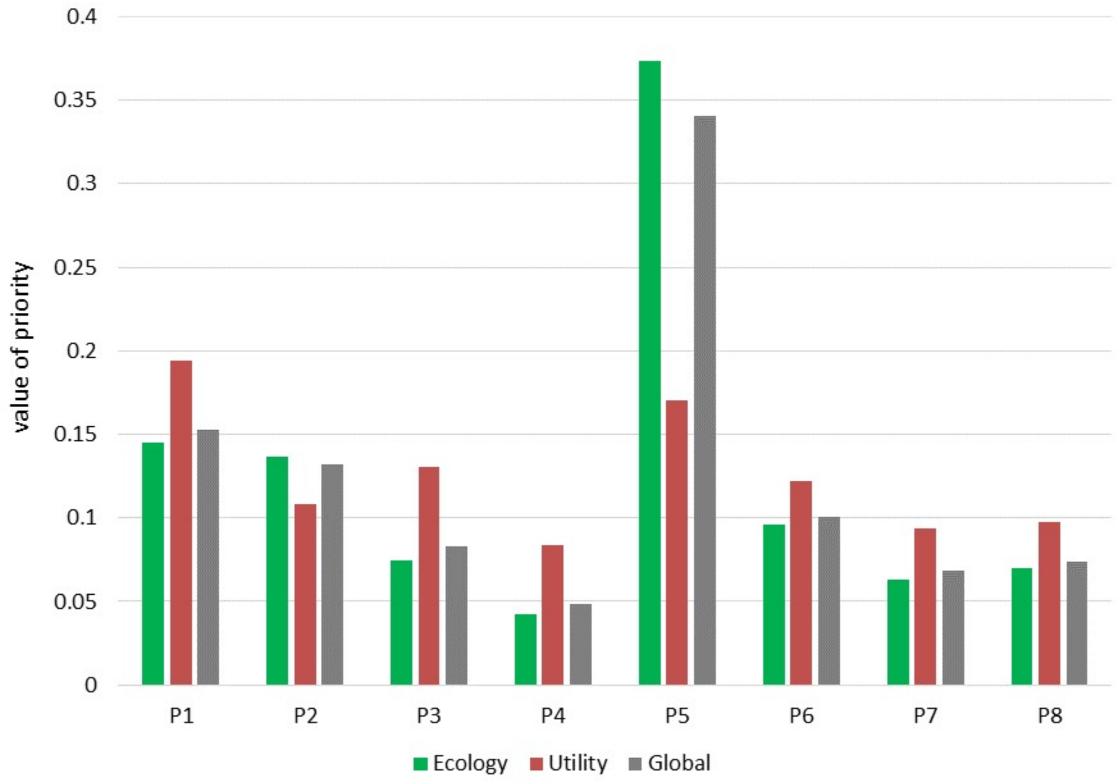

Figure 4. Juxtaposition of values of the local priorities in relation to analyzed cumulated categories and values of the global priorities.

Analysis of the obtained results from performed multicriteria assessment indicates that among analysed points of engine operation, the best controlling results were received for two conditions of lowest engine loads, and hence corresponding to the points P5 and P1 of the engine operation. Wherein, it is worth noting that in assessment of the effectiveness due to the utility criterion, the best results were obtained for the point P1. In general, from the viewpoint of multicriteria assessment for the operating points P7 and P8, it is also possible to highlight comparability of obtained controlling effectiveness. It is also easy to notice, that solely usage of single cumulated category to the assessment of the effectiveness can lead to separate arrangements of the analysed set of results.

7. Summary

Controlling effectiveness of the adjusting parameters in selected points of engine operation varies, while assessment of this effectiveness can be performed due to many criteria. Usage of the multicriteria assessment in evaluation task of the effectiveness enables to take collectively into account a number of the partial criteria, having varied significance. Such assessment of a set of solutions requires determination of values of suitable local priorities. As the effectiveness of cumulated categories varies, values of the global priority decide about final result of the assessment.

Attainment of acceptable overall efficiency of the combustion engine with simultaneous compliance with emission standards is a difficult and labour consuming task, requiring a lot of knowledge and experience. Method of the proceeding presented in this paper is aimed at supporting of decision-making process, needed during partial assessment of results of the controlling parameters of a compression ignition engine. Thus, it can be used in connection with calibration of the engine and can ensure shortening of research work.

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