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RESEARCHES REGARDINGAUTOMOTIVE ENGINE FUNCTIONING

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Abstract. *The paper presents experimental results obtained from tests conducted with an automotive fitted with electronic control Diesel engine. There are highlighted some engine functional characteristics. It is aimed the matter of engine energy efficiency growth. It is approached the matter of parameters influence on engine functioning by using sensitivity analysis, information theory and variance analysis.*
Keywords*: vehicle engine, energy efficiency, sensitivity analysis, variance analysis*

1. INTRODUCTION

Fitting of automotives with on-board computer, electronic control systems, embedded sensors and actuators, the increasingly development of analysis equipments and the theoretical developments of another disciplines have represented the main influence factors regarding the theoretical and experimental study theories of engines functioning [3]. The endowment of engine automotive with lot of actuating and control systems was also possible due to remarkable progress in electronic field and software development.

2. EXPERIMENTAL RESEARCH

The experimental research were conducted with a Ford Focus automotive fitted with supercharged Diesel engine and the “common rail”Diesel fuel injection plant. According to technical specification, the automotives has a fuel consumption of 5.9 liters/100 km for an urban cycle, 4.0 liters/100 km for an extra-urban cycle and a 4.7 liters/100 km fuel consumption for combined cycle [8].
The automotive’s Diesel engine is DOHC (Double Over Head Camshaft), withfour inlinecylinders, 4 valves per cylinder, 1.56 liters capacity displacement, 18 compression ratio, and "common rail" fuel injection. The engine develops a maximum power of 66 kW (90 CP) at 4000 rev/min and a maximum torque of 215 Nm at 1750 rev/min.The engine is equipped with embedded sensors and actuators and the on-board computer assures the functioning, the electronic control and diagnostic [9].
For the acquisition of automotive and engine functional parameters based on sensors have been used the interface and Ford’s FoCOM software [9]. The FoCOM software (from the acronym **Fo**rd **COM**pany) represents a specialised software for the diagnostic of automotives like Ford, Mazda, Lincoln, Mercury and Jaguar and assures during experiments the following:reading functional parameters from the automotive on-board computer memory by connecting the interface with the diagnostic socket (figure 1); viewing data in a graphical or tabular form;data transfer on a computer with FoCOM application (figure 1).
From obtained data have been kept the more significant 100 experimental research, which marks a normal driving during exploitation. The experimental research have taken place on the same rolling track (dry asphalt in good keep) and during the same weather conditions, in the absence of wind.

During experiments, various parameters have beeen measured, among which are mentioned: automotive's speed V [km/h];cyclic flow of fuelc_c [mg/cycle];engine speed$n$ [rev/min];throttleshutters' position, percentage from their maximum opening p [%];engine's torqueM_e [Nm]; fuel pressure from common rail p_c [kPa];intake air pressure p_a [kPa];engine'shourlyintake air consumptionC_a [kg/h];relative amount of recirculatedgas¥ [%]; relative tilt of turbocharger'svanes~ [%].

Figure 1: Experimental research

At these measured parameters we add others obtained by calculus: engine powerP_e [kW], fuel consumption at100 km C_{100} [liters/100 km], engine hourly fuel consumptionC_h [liters/h], specific fuel consumption c_e [g/(kWh)], engine efficiency ¦$_e$ [-], travel speed variation dv/dt [m/s^2], so acceleration/deceleration, traveled space S [m] etc.

In figure 2 areshown the values of fuel cyclic flow and engine torque, in continuous representation (usually used, but unreal) and in discrete representation (rarely used, but real, the experimental data having a discrete character).Discrete representation, the real one, allows a more easy viewing of ranges with the most values for the targeted parameter. For example, from figure 2a results that more than a half of cyclic flow of fuel values (54.6%) are in the range 10-20 mg/cycle.Likewise, from figure 2b we can see that few values (4.3%) are in the range where engine torque is high, in graph are shown both maximum experimental value and maximum value from engine technical specification [8].

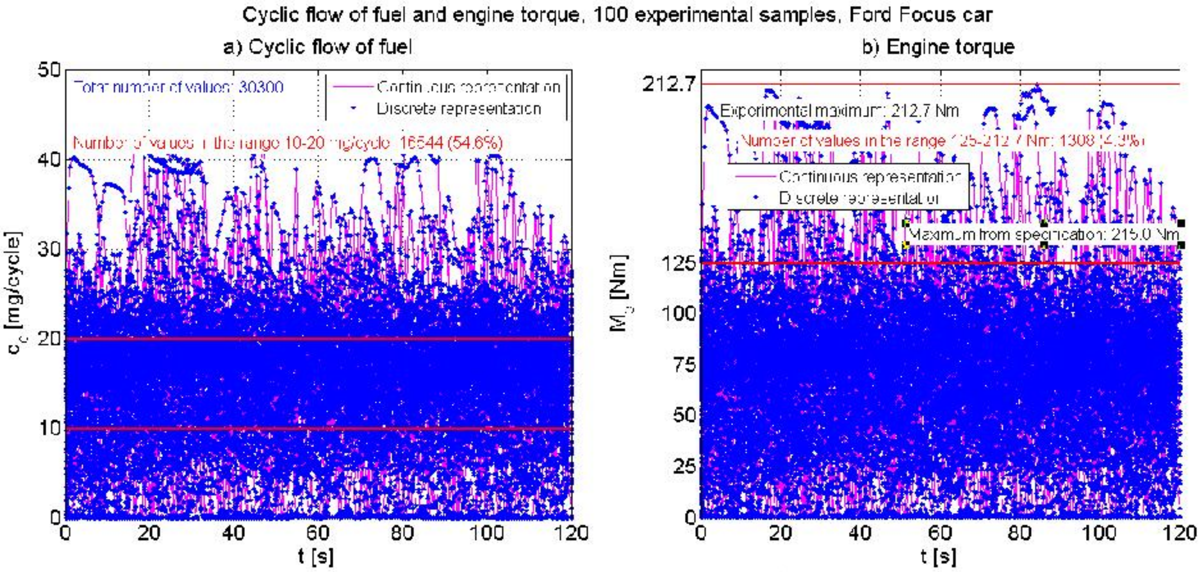

Figure 2: Cyclic flow of fuelandengine torque

3. THE STUDY OF FACTORS INFLUENCE ON ENGINE FUNCTIONING

The more and more drastic requests regarding dynamics and fuel saving performances that are currently assessed to engine automotives, imply a thourough study regarding the influence of various factors on engine functioning.In specialty literature can be found quantitative and qualitative estimations towards the influence of functional parameters, adjustment, design and automotive operation performances. It must be mentioned that in specialty literature the study of different parameter's influence is made based on a restrictive methodology such as: for the study of one parameter influence it is considered that the others are constant, which is obviously unreal.

The study performed during this paper eliminates the mentioned limitation regarding the hypothesis that other factors, beside the one targeted, remain constant, especially that in case of automotives equipped with on-board computer there are pronounced functional interfaces. For quantitative highlighting of parameters influence on engines functioning, there are used the correlation analysis, dispersional analysis, information theory and sensitivity analysis [1; 2; 4; 5; 6; 7].

In ***correlation analysis***, for highlighting if functional parameters are independent or not and for establishing the character (linear or non-linear), it is frequently used the *correlation coefficient*°, defined by ratio[3]:

$$^\circ_{xy} = \frac{R_{xy}(0)}{\sqrt{R_{xx}(0)R_{yy}(0)}} \qquad (1)$$

with the values $^\circ \in [-1;1]$, a perfect linear dependency is for°²=1. If°:=1,then there is a perfectly direct linear dependency, and if°:=-1 then there is a perfectly indirect linear dependency; if $0 < {}^\circ \leq 1$ there is a directly non-linear dependecy, and if $-1 \leq {}^\circ < 0$ there is an directly non-linear dependency. To conclude, if°:=0, then the two parameters *x*and*y*are independent; obviously, if $^\circ \neq 0$ parameters are dependent. In addition, in formula (1), at numerator is the intercorrelation function with the origin of discrete time, meaning for²:=0, and under the radical are intercorrelation functions still for ²:=0.

For example, in figure 3are presented the values of correlation coefficients for the 100 experiments of Ford Focus automotive; the factorial sizes (the influence factors) are fuel pressure$p_c$and recirculated gas ¥, and the resulted parameter is engine torqueM_e.

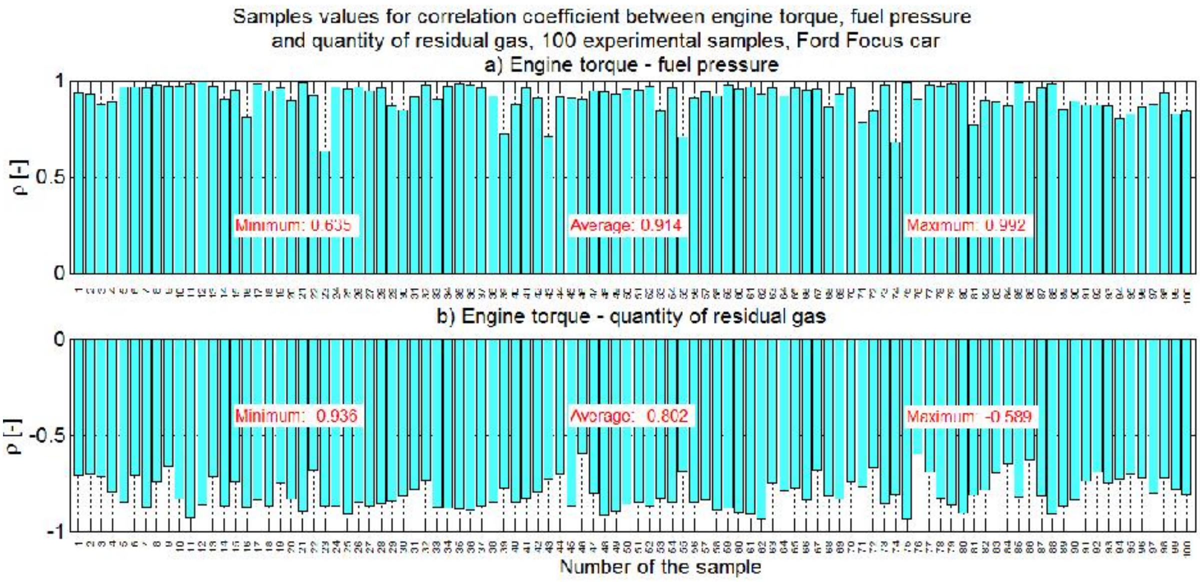

Figure 3: Correlation analysis

As it can be seen fromfigure 3, for every experimental sample the correlation coefficient is not null so the targeted parameters are dependent, which would be expected from a functional point of view. Also, because the correlation coefficients are subunitary for every test, it results that between these parameters are more or less non-linear dependencies; from the two, the most pronounced non-linear dependency is between engine torque and the quantity of residual gas, the correlation coefficients having smaller values, including the average for all the tests °:=-0.802 as against to°:= 0.914 in the first case. The existence of non-linear dependencies leads to the conclusion that engine functioning must be described by using non-linear mathematical models for a higher

accuracy.
In addition, the graph from figure 3a shows that between engie torque and fuel pressure there is a direct dependency, the correlation coefficients have positive values; so, when the fuel pressure increases, engine torque increases and backwards. But the graph from figure 3b shows that between the engine torque and the quantity of residual gas there is an indirect dependency, the correlation coefficients having negative values; so, when the quantity of residual gas increases, the engine torque decreases and backwards.
Informational analysisof engine functioning, based on experimental data, allows establishing relevant parameters, so those factors with the highest influence on the targeted parameters. Informational analysis of engine functioning is based on two main concepts from information theory: entropy and information [1; 5; 7].So, *the entropy* represents the product of probability *p* and information*I*for the entire events $x_i \in X$:

$$H(X) = \sum_{i=1}^{n} p(x_i) I(x_i) \quad \Rightarrow \quad H(X) = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i) \qquad (2)$$

and*mutual information* is established with a formula that also contains conditional entropy:

$$I(X;Y) = H(X) - H(X|Y) \qquad (3)$$

Mutual information represents a basic concept for the study of systems dynamics (engine functioning) and *represents a measure of interdependency* between variables.Because of this, the variables with the highest influence are defined by the highest mutual information; these are called relevant variables, attached to the concept of relevance.From mentioned reasons, it is considered that information theory represents an extension of classical correlation, and the mutual information represents a measure of relevance.
For example, in figure 4 is presented the graph with the results of informational analysis when the engine torque is the resulting parameter (placed in the upper part) and by taking into account the 6 factorial sizes (influence factors): throttle shutters' position, engine speed, fuel pressure, intake air pressure, quantity of recirculated gas andrelative angle tilt of turbocharger'svanes.

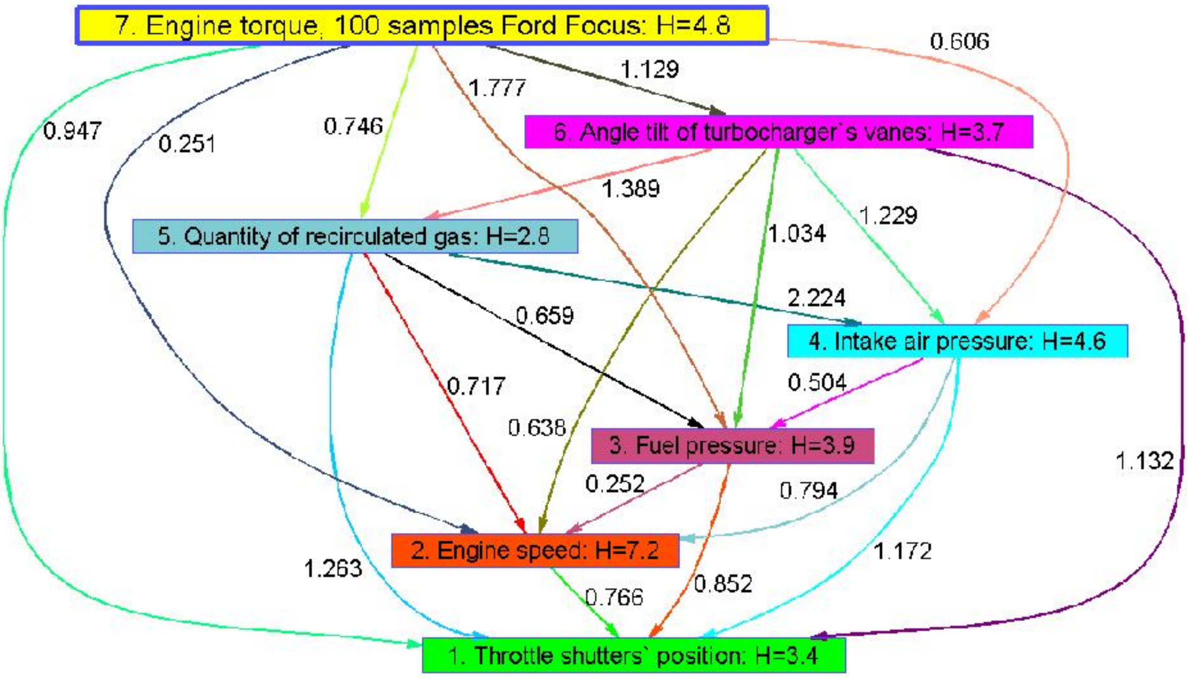

Figure 4: Informational analysis

In graph's assembly from figure 4 are shown the values of *H*entropy. On the graph's bend are written down the values of mutual information between two *I* parameters. It can be seen that the first two relevant variables (with the highest inflence on engine torque) are fuel pressure (mutual information with the engine torque of 1.777 bits) and tilt angle of vanes(*I*=1.129 bits).
In figure 4 are also shown the mutual informations between the 6 factorial sizes; it is determined that the biggest mutual information is between intake air pressure and quantity of recirculated gas, of2.224 bits, which exceeds

the ones mentioned above; this aspect confirms the necessity that the study of engine functioning should also target the mutual influence between different factors, not only between them and the targeted parameter.

Sensitivity analysisallows highlighting the attribute of a resulting parameter to modify it's value because of a factorial sizes.Similar to correlation analysis, if there is a single factorial sizes, then is targeted the simple sensitivity, otherwise it is a multiple sensitivity; in the first case is defined local sensitivity (the classical one, which uses the sensitivity function), in the second case is defined the global sensitivity, which is measured by Sobol [4]. In this second case, Sobol coefficient (noted*S*) represents the proportion between parameter's dispersion and total dispersion of resulting parameter; in conclusion, there is the ratio:

$$\sum_{i} S_i + \sum_{i}\sum_{j>i} S_{ij} + \sum_{i}\sum_{j>i}\sum_{k>j} S_{ijk} + ... = 1 \tag{4}$$

where for the influence factor*i*there is the Sobolfirst ordercoefficientS_i(or main Sobol coefficient), for the interaction between factors*i*and *j*there is the Sobol second order coefficient S_{ij}etc. As it can be seen, global sensitivity also considers interactions between targeted factors, similar to informational analysis.

For example, in figure 5 is presented the Sobol first order coefficient for engine torque M_e, engine power P_e, cyclic flow of fuel$c_c$and hourly fuel consumption$C_h$as resulting parameters; the influence factors are throttle shutters' position*p*, engine speed*n*, fuel pressurep_c, intake air pressurep_a, quantity of recirculated gas¥andrelative tilt of turbocharger'svanes~.

As it can be seen,for example, for figure 5a and figure 5c, engine torque and cyclic flow of fuelare the most sensitive to fuel pressure variation (*S*=0.837and *S*=0.864).

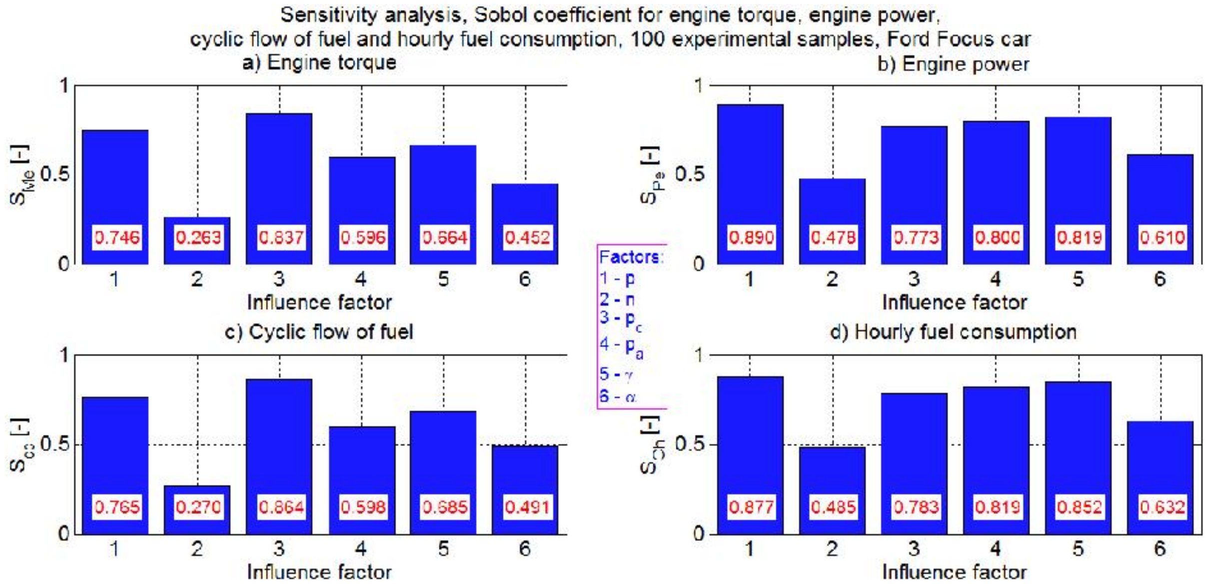

Figure 5: Sensitivity analysis

The study of different factors influence also uses***variance analysis*** (ANOVA – **AN**alyse **O**f **Va**riance, MANOVA – **M**ultivariate **AN**alyse **O**f **VA**riance); dispersion has a significant relevance in the analysis of different factors influence on the progress of a dynamic process, here is engine functioning [2; 6].

The english statistician and mathematician Ronald Fisher, founder of variance analysis, proved that by estimating dispersion of acharacteristic, influenced by a factor, then by eliminating the influence and comparing the two dispersions, there are obtained quantitative informations about this influence. In consequence, variance analysis means comparing two types of dispersion, factorial and residual. If factorial dispersion is bigger than residual dispersion, then the current factor has a noticeably influence on the targeted process.Backwards, if factorial dispersion (individual or interaction with another factor) is smaller than the residual one, then the factor has a sloppy influence on the targeted process. Practically, this comparison can be made by establishing percentage contribution for every factor and the residual for total dispersion. For example,in figure 6are presented the results after applying generalized MANOVA algorithm (are being considered the targeted factors and interactions between them), through the study of influence on cyclic flow of fueland hourly fuel consumption for 4 factors, including the interactions between them.

From figure 6it can be determined that in both cases, the residual dispersion values (with 1.7% and 0.74%)are smaller than dispersions values associated with fuel pressure (66.8% and 50.9%), tilt angle of the vanes (18.5% and 19.5%), quantities of residual gas (9.49% and 27.4%)and interactions between throtle shutter's positionand

quantity of residual gas (2.18% and 0.96%).
So, in both cases,fuel pressure has the biggest influence on cyclic fuel variation and hourly fuel consumption.

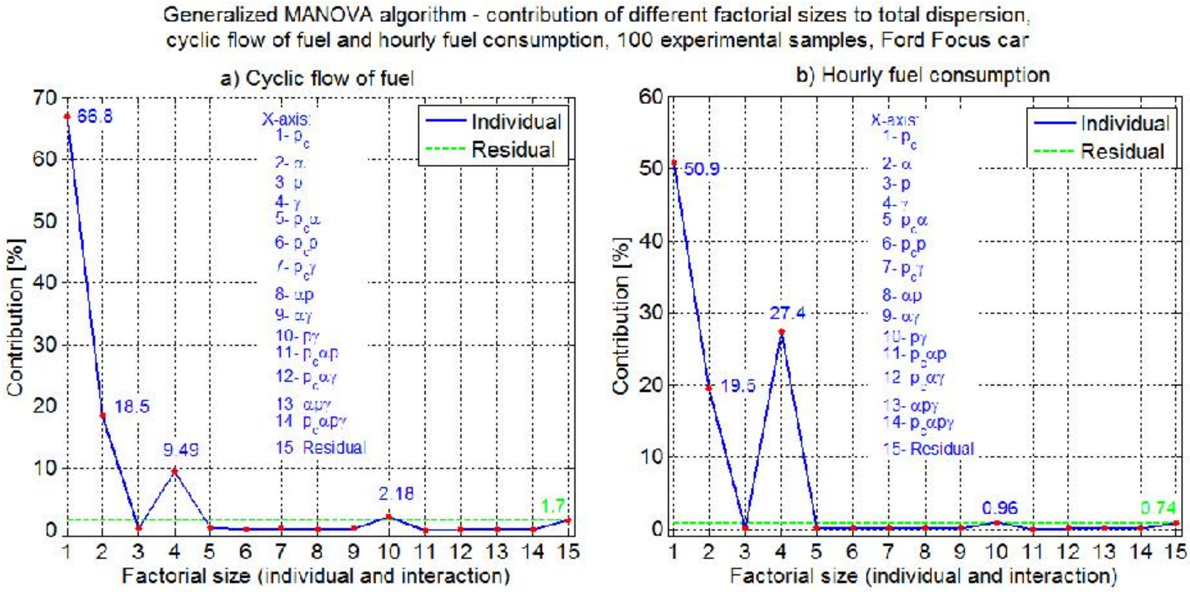

Figure 6: Variance analysis

4. CONCLUSIONS

The study of automotive engine functioning based on experimental data allows highlighting different features if there are used methods and algoritms specific to systems dynamics.
From the above results that the study of different factors influence on engine functioning must also take into account the interactions between factors, as well as the fact that factorial sizes vary simultaneously during functioning, these two represents main differencies towards classical study from specialty literature.

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