The comparative study of vehicles engine in different functioning situations

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Abstract: The paper presents a comparative study of a Diesel engine functioning in different situations and at different partial loads and engine speeds. There are shown graphs of some experimental results, obtained by using concepts and algorithms from mathematical statistics. It is presented a study of functional factors influence on engine dynamics and fuel saving, by using correlation analysis, variance analysis, information theory and sensitivity analysis. There are highlighted characteristics of vehicle driving in urban and extra-urban environment.

1. Introduction
The study of engine dynamical behavior has developed new possibilities due to electronic control of engine parameters. The in-depth of phenomenas that appear during functioning can be studied based on informations sent from on-board computer, which implies a systemic and interdisciplinary handling of modern engine dynamics, approach resulted from the engine structural and of control complexity. In view of all this, the paper performs an analysis of experimental data acquired from embedded sensors which were stored by the on-board computer; the analysis of experimental data offers the possibility to establish engine dynamics and fuel saving performances.

2. Experimental research
Experimental researches were conducted with a Ford Focus automobile equipped with a supercharged Diesel engine and a “common rail” supply unit. For the acquisition of engine and vehicle functional parameters were used the Ford’s FoCOM software and interface [1, 2]. The tests allowed the acquisition and storage of a certain number of experimental data, whereat are added those obtained by calculus. From all data were kept the 80 most significant experimental samples, which marked a normal driving; from these, 40 samples represent urban driving, and the other 40, extra-urban driving. One sample contains 4000 values for each parameter, the time period is of 400 s; results a measuring rate of 10 values/s.

3. Data statistical processing
Follow-up are presented some of the results, which contain instantaneous values of functional parameters, as it is presented in figure 1 for vehicle driving speed $V$ and in figure 2 for engine speed $n$. Likewise, by using first order statistical characteristics, in graphs were are also presented minimal, average and maximal
values of vehicle speed and engine speed, in case of urban and extra-urban driving. Graphs from figure 1 and figure 2 show that in case of extra-urban environment the values of vehicle speed and engine speed are higher than in urban environment, which was expected.

For example, from figure 1a results that in case of urban environment all 160000 values are in the range 0-70 km/h; instead, from figure 1b it can be observed that in extra-urban environment 86.8% of all values are in a superior interval, meaning in the range 70-130 km/h.

Similarly, from figure 2 results that in urban environment 34.6% of values are in the range 1500-2500 rev/min, and in case of extra-urban environment there are 85.6% of values within the interval.
In figure 3 are presented instantaneous, minimal, maximal and average values of throttle shutter’s position \( p \), stated as a percentage of the maximum opening. As it can be seen from graphs, throttle shutter’s position has also higher values in extra-urban environment relative to urban environment.

![Instantaneous acceleration pedal position values, 40 urban samples and 40 extra-urban samples, the Ford Focus car](image)

**Figure 3.**

In figure 4 are shown average values of fuel consumption; graphs from the left illustrate engine hourly fuel consumption \( C_h \), and those from the right contain fuel consumption at 100 km \( C_{100} \). From these graphs

![Mean values on samples of fuel consumption, 40 urban samples and 40 extra-urban samples, the Ford Focus car](image)

**Figure 4.**
results a higher hourly consumption in case of urban driving, and a fuel consumption at 100 km lower in case of extra-urban driving.

The explanation results from formula [3]:

\[
C_{100} = 100C_s/V
\]  

(1)

Indeed, even if hourly consumption is higher for extra-urban driving, fuel consumption at 100 km is lower due to higher speeds in this case (the effect of speed is predominant).

In figure 4 are shown the values of fuel consumption at 100 km, from vehicle’s technical specifications 5.9 liters/100 km for urban driving and 4 liters/100 km for extra-urban driving.

Graphs from figure 5 present average values of the quantity of recirculated gas \( \gamma \) and of rotational angle of turbine vanes \( \alpha \). From these graphs it can be observed that for all samples, the two sizes are smaller in case of extra-urban driving.

![Figure 5.](image)

In figure 6 are presented the histograms of engine torque \( M_e \) and engine power \( P_e \) in case of urban and extra-urban driving. Upper graphs show a placement of the two sizes closer to lower values in case of urban driving; in lower graphs the sizes are closer to average values in case of extra-urban driving.

Likewise, from figure 6 it can be seen that the two sizes are subject of normal distribution, which confirms that engine torque motor from figure 7 with the values of repartition function \( F(x) \) where is also applied the Smirnov-Kolmogorov test, noted S-K [3, 4], as well as from figure 8 where are shown the values for density of probability \( f(x) \). As it can be seen from figure 7, the experimental curve is different from the ideal one and the data are not subject of normal distribution.

Likewise, as it can be seen from figure 8, curve functions \( f(x) \) do not have a single maximum placed at the average value \( M_{\text{ave}} \), meaning the so called Gauss bell; in the lower part of graphs from figure 8 it is shown the placement of experimental values in order to present a sugestive image for density of probability.
Figure 6.

Histogram of engine torque and engine power, 40 urban samples and 40 extra-urban samples, the Ford Focus car

Figure 7.

Verification of compliance with the normal distribution law/Gauss, engine torque, the Ford Focus car

Figure 7.
The paper contains a study of main factors influence on sizes that define engine dynamics and fuel saving performances. For a quantitative highlighting of targeted sizes on engine functioning there can be used correlation analysis, variance analysis, information theory and sensitivity analysis.

4.1. Correlation analysis. In order to highlight if functional sizes are independent or not and to establish the dependency between sizes (linear or non-linear), it is frequently used the correlation coefficient \( \rho \), defined by formula [3,4]:

\[
\rho_{xy} = \frac{R_{xy}(0)}{\sqrt{R_{xx}(0)R_{yy}(0)}}
\]

with values \( \rho \in [-1; 1] \), a perfect linear dependency if \( \rho^2 = 1 \). If \( \rho = 1 \) then there is perfect direct linear dependency, and if \( \rho = -1 \) there is perfect indirect linear dependency; if \( 0 < \rho \leq 1 \) there is a direct dependency, and if \( -1 \leq \rho < 0 \) there is an indirect dependency. Finally, if \( \rho = 0 \), the two sizes \( x \) and \( y \) are independent. So, if \( \rho^2 \) is far away of unitary value (without reaching the null value), the highest the non-linearity.

In addition, in formula (2), at numerator is the intercorrelation function in the origin of discrete time, meaning for \( \tau = 0 \), and under the radical are intercorrelation functions for \( \tau = 0 \).

For example, in figure 9 are presented values of correlation coefficient in case of urban driving; factorial sizes (influence factors) are fuel pressure from the common rail \( p_c \), intake air pressure \( p_a \), throttle shutter's position \( p \) (engine load) and engine speed \( n \), and resultative size is engine torque \( M_e \).

As it can be seen from graphs, there is no experimental sample at which the correlation coefficient is nul and because all sizes are not independent, which was functionally expected. Likewise, because for all samples the correlation coefficients are subunitary, it can be concluded that between sizes there are non-
linear dependencies; the most pronounced non-linear dependency is between engine torque and engine speed, the correlation coefficients having the lowest values, including the mean for all samples $\rho=0.351$.

This final aspect leads to the conclusion that engine functioning must be described by non-linear mathematical models in order to ensure high precision.

![Figure 9.](image)

**Figure 9.**

4.2. Variance analysis. The study of some factors influence also uses variance analysis (ANOVA – ANalyse Of Variance, MANOVA – Multivariate ANalyse Of VAriance); dispersion has an important role in the analysis of factors influence on a dynamic process. English matematician and statistician Ronald Fisher, the founder of variance analysis, proved that by estimating variance of a characteristic influenced by a factor, and by removing that influence and comparing the two variances, there can be obtained quantitative informations regarding the influence.

In conclusion, variance analysis consists of comparing two types of variances, factorial and residual. If factorial variance is higher than the residual one, the respective factor has a sensible influence on the targeted process. On the other hand, if factorial variance (individual and of interaction with another factor) is lower that the residual one, the factor has a neglectable influence on targeted process. Practically, this comparison can be made by establishing percentage contribution of each factor and residual in case of total variance [3, 5, 6].

In figure 10 are presented results after applying generalized MANOVA algorithm (there are considered the targeted sizes and their interactions), by the study of throttle shutter's position influence $p$ and engine speed $t$ on engine torque $M_e$. From figure 10 it can be seen that in both cases, variance of engine speed is higher that the residual one (89.2%, respective 79.5%) as well as the variance of throttle shutter’s position (9.9%, respective 14.7%). So, in both cases, throttle shutter’s position (considered the engine load) has the highest influence on engine torque variance. From graphs it can also be observed a lower influence on engine torque variance given by the interaction between throttle shutter’s position and engine speed.
4.3. Informational analysis. The study of factors influence also uses informational theory, which allows establishing significant parameters that define engine functioning. Informational analysis is based on two main concepts from information theory: entropy and mutual information [3, 7, 8, 9, 10, 11]. Mutual information represents a concept regarding the quantitative estimation of uncertainty attenuation, meaning the increase in prediction. The higher the values of mutual information, the lower the uncertainties, meaning higher predictions. Considering this, mutual information represents a basic concept for the study of systems dynamics and represents a measure of interdependencies between variables. Therefore, in establishing mathematical models must be chosen those variables characterized by the highest mutual informations, which assures the highest predictions; those are called significant variables, attached to the concept of relevance. Considering all reasons mentioned above, information theory represents a generalisation of classical theory, and mutual information represents a measure of relevance.

For example, in figure 11 is presented the graph containing results of informational analysis in case of engine torque as a resultant parameter (placed in upper part) and by considering 6 factorial sizes (influence factors): engine load (through throttle shutter’s position \( p \)), engine speed \( n \), fuel pressure from the common rail \( p_c \), intake air pressure \( p_a \), quantity of recirculated gas \( g_74 \) and rotational angle of turbine vanes \( \alpha \).

In graphs’ joints are shown the values of entropy \( H \). It can be observed that the highest entropy is owned by engine speed, of 7.1 bits, and the lowest belongs to intake air pressure: \( H=2.8 \) bits; according to those mentioned it results that the usage of engine speed in dynamic calculus has the effect of most reduced prediction. On graphs’ bend are written the values of mutual information between two sizes \( I \). It can be seen that the first two relevant variables (with the highest influence on engine torque) are throttle shutter’s position (a mutual information with engine torque of 1.165 bits) and fuel pressure (\( I=0.485 \) bits).

In figure 11 are also shown mutual informations between the 6 factorial sizes; it can be observed that that the highest mutual information is between fuel pressure and rotational angle of vanes, of 2.213 bits, which also exceeds those mentioned above; this aspect confirms the necessity that engine’s functional study also target the influence between different factors, not only the influence of factors on resulting parameter.

Similarly, it is made an analysis in case of extra-urban driving, the first two significant sizes being the same as in case of urban driving.
It should also be observed that variance analysis targets only parameters variance, and informational analysis targets the entire parameter, not only the variance.

5. Engine energy efficiency
For a detailed study of engine functioning it should be targeted its energy efficiency, meaning both engine dynamics and fuel saving [3].

For the study of energy efficiency can be established different assessing criteria, which can show the intake of energy in order to obtain certain dynamical performances.

For example, in figure 12 is presented the fuel consumption, expressed in mililiters, needed to obtain an engine power of 1 kW and an engine torque of 1 Nm. In figure 13 are shown mean values of the ratio between vehicle kinetic energy (meaning the energy used for actual driving) and the energy introduced with the fuel.

From figure 12 it can be seen that in order to obtain a unity of power and torque, it is consumed a higher quantity in case of urban driving; so, energy efficiency is higher in case of extra-urban driving.
In figure 13, the ratio between vehicle kinetic energy $W_{cin}$ and energy introduced by fuel $W_f$ is established with ratio:

$$k_c = \frac{W_{cin}}{W_f} \cdot 100 \%$$  \hspace{1cm} (3)
where:

$$W_{cin} = m_a v_a^2 / 2; \quad W_i = C_i Q_i S / V$$

(4)

and in which there are noted:

- $m_a$ and $v_a(V)$ – autovehicle weight and speed;
- $S$ – distance covered;
- $Q_i$ – fuel inferior calorific power;
- $C_i$ – fuel hourly consumption.

Graph from figure 13 shows that for the 40 experimental samples in urban environment, from the energy introduced by fuel only 10.1\%-30.7\% it is used for actual driving; the mean of energy used at all 40 samples is 18.7\%. Similarly, from figure 13 results that for all 40 samples in extra-urban driving, from the energy introduced by fuel only 21.4\%-40.8\% it is used for actual driving; the mean of energy used at all 40 samples is 33.4\%. In conclusion, even for this assessment criterion, energy efficiency is higher in case of extra-urban driving. It must be mentioned that the values presented are also confirmed by specialty literature from autovehicle field, proving so its poor energy efficiency.

6. Conclusions

The equipment of current automobiles with sensors and actuators embedded from fabrication and with an on-board computer, allows conducting complex studies, which go deep in the core of highly rapid dynamic processes that are specific to engine functioning.

Assessment criteria for engine fuel saving, currently used in specialty literature, do not satisfy the requests of a study regarding energy efficiency, that is why there must be established criteria specific to this issue.

The study of factors influence on engine functioning must also take into account interactions between factors, but also the fact that factorial sizes vary simultaneously during driving, these two are the main differences from the classical study presented in specialty literature.

7. References

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