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# The Influence of Functional Factors on the Performance of Motor Vehicles Moving in Urban and Extra Urban Environments

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**ABSTRACT:** The paper presents the study of the influence of functional factors on the performance of vehicles traveling in urban and extraurban areas. For this purpose, informational analysis, variance analysis and sensitivity analysis are used. The study considers that all functional factors vary simultaneously and influence each other, which is in line with the findings during the operation of vehicles. For the study, the data obtained from the experiments performed with Ford Focus and Volkswagen Touareg cars, both equipped with a diesel engine, as well as with the Logan Laureate car equipped with a petrol injection engine, are used.

**KEYWORDS:** motor vehicle, informational analysis, variance analysis, sensitivity analysis, Sobol index.

## I. INTRODUCTION

The study of the influence of various factors on the operation of the car engine was a permanent concern of specialists in the field. In the literature there are assessments, both quantitative and especially qualitative, regarding the influence of functional, regulatory, constructive and operational factors on the power performance, fuel consumption and pollutant emissions of vehicles [5,7,8]. It should be noted, however, that in the literature the study of the influence of various factors is performed according to a restrictive methodology, namely: to study the influence of only one factor is considered that all others remain constant, which is obviously inconsistent with reality. In the paper this restriction is eliminated, especially since in the case of cars equipped with on-board computer there are accentuated functional interdependencies, the experimental researches confirming that the parameters are not constant in time.

Consequently, the paper aims to study the influence of factors (also called factorial quantities) on vehicle performance. For this purpose, the experimental data are used, namely those functional quantities that are taken from the on-board computer of the vehicle, specifically of cars equipped with diesel or gasoline engines; therefore, the functional dimensions measurable during the movement of the vehicles are concerned, such as: speed  $n$  and engine load (last by the intake air pressure  $p_a$  or the position of the accelerator pedal  $p$ , or the position of the throttle valve  $\xi$ ), ignition advance  $\beta$ , injection time  $t_i$ , fuel pressure  $p_c$ , angle of inclination of the turbine blades  $\alpha$ , the amount of recirculated gases  $\gamma$  etc.

The quantities on which the influence of the mentioned factors is targeted can be the fuel consumption (by the fuel consumption per 100 km traveled  $C_{100}$ , the hourly fuel consumption  $C_h$ , the specific effective fuel consumption  $c_e$  etc.), the power performances (by the engine power  $P_e$  and the engine torque  $M_e$ ), vehicle speed  $V$  etc.; these are resultant quantities.

## II. EXPERIMENTAL RESEARCH

To study the influence of functional factors on vehicle performance, experimental research was conducted with a Ford Focus car and a Volkswagen Touareg II 3.0 V6 TDI car, both equipped with supercharged diesel engine and common-rail fuel supply system.

Experimental research was also carried out with a Dacia Logan Laureate car equipped with a petrol injection engine.



For the acquisition of data from the on-board computer, the Ford interface and software were used. For Volkswagen Touareg was used the VCDS application developed by Ross-Tech, which is the specialized diagnostic software for the Volkswagen group. For the Logan Laureate car, the Clip tester and the related software from Renault were used. From the purchased data, 40 samples from the urban environment and 40 samples from the extraurban environment were retained for each car, more significant for the purposes pursued.

For example, fig.1 shows the instantaneous values of the speed of the Ford Focus car when it travels in urban and extra urban areas and in fig.2 the values of the speed of the Volkswagen Touareg II 3.0 V6 TDI car.

Fig. 1 shows that in urban areas, the speed of the car varied in the range of 1-69 km/h with an average of 36.4 km/h, and in the extraurban environment in the range of 51.6-130 km/h with an average of 97.3 km/h. It is found that in the extraurban environment the car speeds were higher than in the urban environment, on average 2.67 times. It is also observed that 86.8% of the values in the extraurban environment are higher than those in the urban environment.

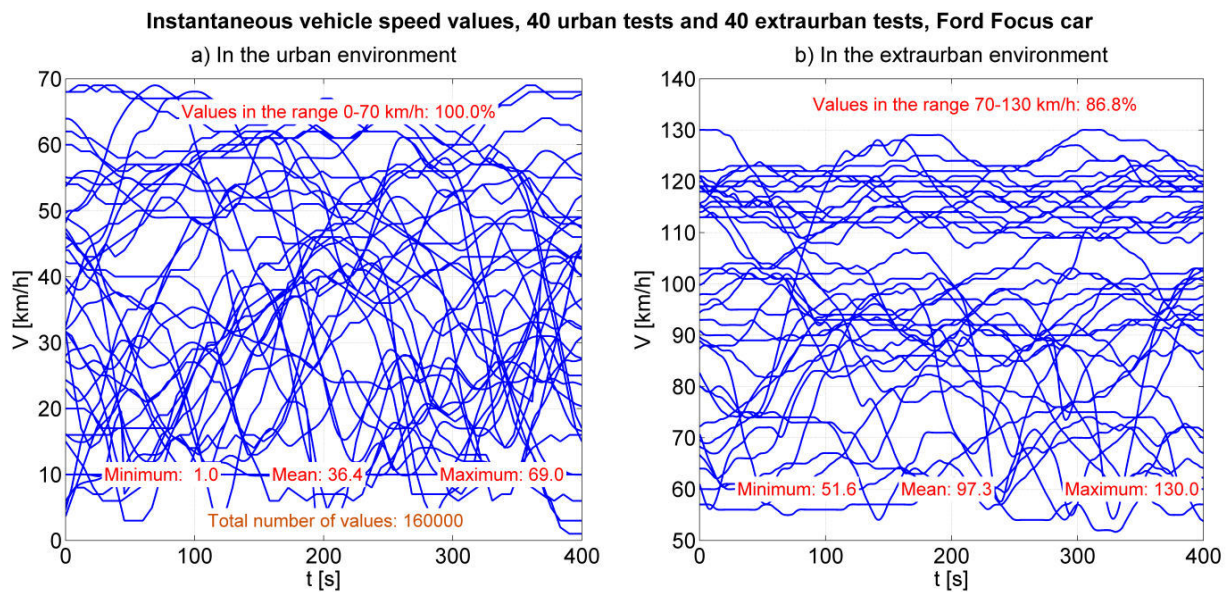


Fig.1. Instantaneous speed values of the Ford Focus car

Fig. 2 shows that in the urban environment the speed varied in the range of 23-58.1 km/h with an average of 41.9 km/h, and in the extraurban environment in the range of 60.6-145.3 km/h with an average of 105.3 km/h. It is found that in the extraurban environment the speeds of the car were higher than in the urban environment, on average 2.51 times. It is also observed that all values in the extraurban environment are higher than those in the urban environment.

As can be seen, in fig.1 all the 40 tests were represented superimposed, and in fig.2 they were shown one after the other.



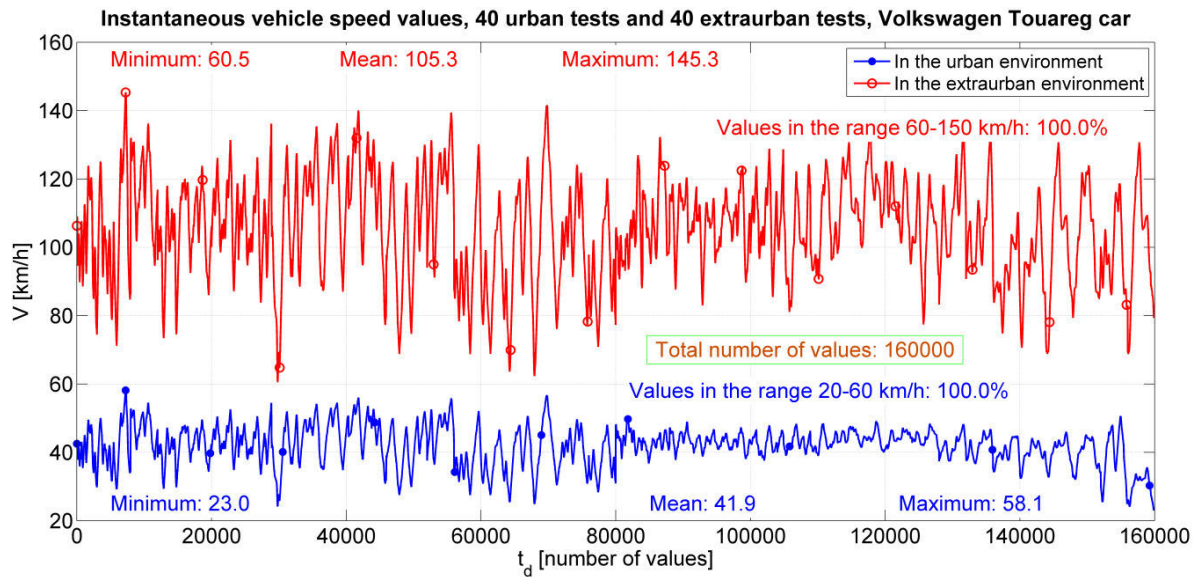


Fig.2. Instantaneous speed values of the Volkswagen Touareg II 3.0 V6 TDI car

### III. INFORMATIONAL ANALYSIS OF THE VEHICLE DYNAMICS

Informational analysis uses the concepts of entropy and mutual information [3, 6]. Thus, in order to characterize the uncertainty in the occurrence of an event, the concept of entropy is used. The higher the entropy value, the more pronounced is the uncertainty and therefore the lower the prediction.

Mutual information shows the dependence between two variables; the higher its value, the greater the dependence. For this reason, when deducing mathematical models, those variables are chosen in which the mutual information is the largest, which ensures the highest predictions; these quantities are the relevant variables.

As it is known, information is the fundamental concept in prediction and is characterized by a distribution of probabilities  $p$  attached to a set of events that occur. The information contained in  $n$  events  $x_i \in X$  is established using the relation:

$$I(x_i) = -\log_2 p(x_i) \tag{1}$$

As can be seen from this expression, if  $p(x_i)=1$ , then  $I(x_i)=0$ ; therefore, the event that appears for sure does not contain any information.

In order to characterize the uncertainty in the occurrence of an event, the concept of entropy is used, which represents the product between probability and information on all events  $x_i \in X$  :

$$H(X) = \sum_{i=1}^n p(x_i)I(x_i) \tag{2}$$

or, having regard to relation (1):

$$H(X) = -\sum_{i=1}^n p(x_i) \log_2 p(x_i) \tag{3}$$

We now consider two variables  $X$  and  $Y$ , for which there is the common probability density  $p(x, y)$ . In this case, the entropy common to the two variables is calculated with a relation similar to expression (3):

$$H(X, Y) = -\sum_x \sum_y p(x, y) \log_2 p(x, y) \tag{4}$$

Conditional entropy is also defined:

$$H(X|Y) = -\sum_x \sum_y p(x,y) \log_2 p(x|y) \tag{5}$$

The mutual information is established with the relation:

$$I(X;Y) = H(X) - H(X|Y) \tag{6}$$

and which is a quantitative measure of reducing the uncertainty of parameter  $X$  if parameter  $Y$  is known. An example of informational analysis aims at the dynamism of the Ford Focus car, through its acceleration, compared to driving in urban areas (fig.1) and in extraurban environments (fig.2). In the nodes of the graph in fig.3 and fig.4 are presented the values of the entropy  $H$ , and on the arcs of the graph the values of the mutual information  $I$ .

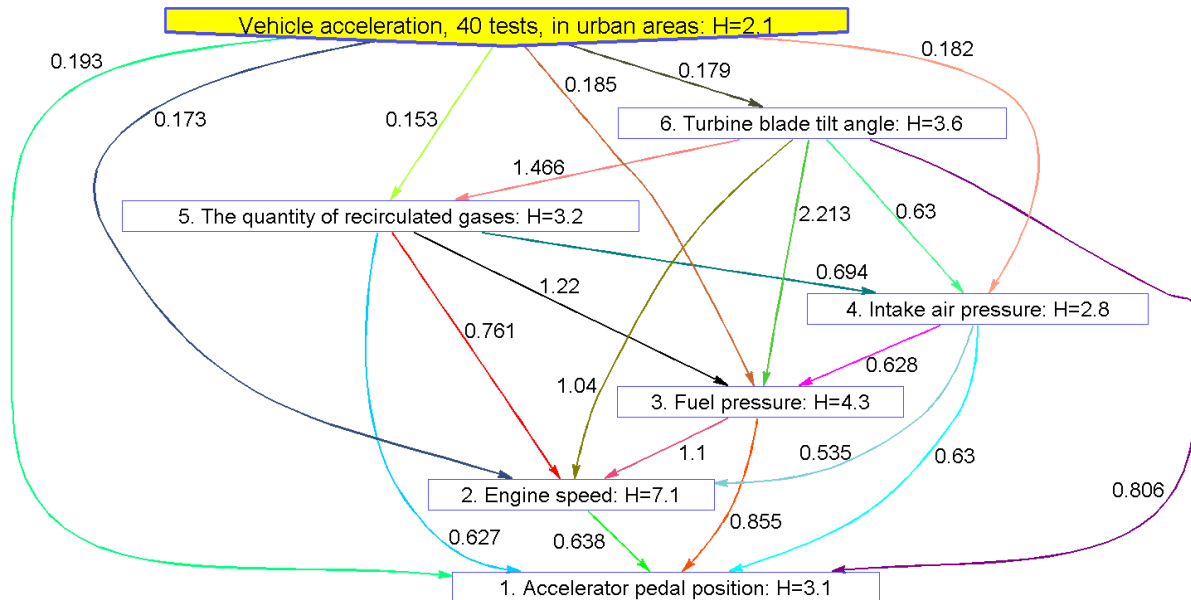


Fig.3. Information analysis, the acceleration of the Ford Focus car when driving in urban areas

The 6 factorial quantities (functional factors, influencing factors) were mentioned in the nodes of the graph, and in the upper part is the resultant quantity, here the acceleration of the vehicle.

Fig. 3 shows that in the urban environment, the acceleration is most influenced by the position of the accelerator pedal (0.193 bits), followed by the fuel pressure in the common rail (0.185 bits) etc.; acceleration is least affected by the amount of recirculated gas (0.153 bits).

Fig. 4 shows that in the extraurban environment, the acceleration is most influenced by the fuel pressure (0.198 bits), followed by the position of the accelerator pedal (0.171 bits) etc.; acceleration is least affected by engine speed (0.103 bits).

It should also be mentioned that the graphs presented highlight not only the influences of functional factors on the parameters that define the performance of vehicles. Indeed, these graphs also show the mutual influences between two functional factors. For example, Fig. 4 shows that between the amount of recirculated gases and the intake air pressure there is a significant influence, quantitatively equal to 2.022 bits.

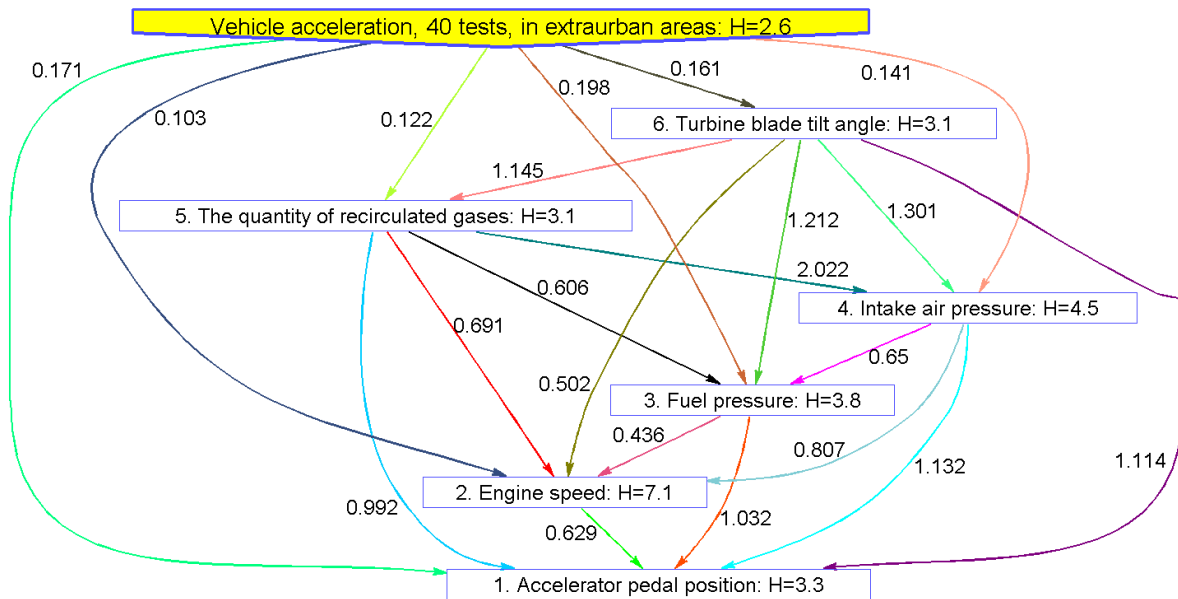


Fig.4. Information analysis, the acceleration of the Ford Focus car when driving in extraurban areas

#### IV. VARIANCE ANALYSIS OF THE VEHICLE DYNAMICS

Variance analysis, developed by English statistician and mathematician Ronald Fisher, uses size dispersion. For this purpose, the variance of each functional factor is compared with the residual variance (modeling error). If the variance of a factor is greater than the residual variance, then that factor has a significant influence on the variation of the resulting resultant quantity. Conversely, if the variance of a factor is smaller than the residual variance, then that factor does not have a significant influence on the variation of the resultant quantity, so this influence can be neglected. If a multivariable array of parameters [1, 4] is targeted, then multivariate variance analysis (MANOVA - Multivariate ANalysis Of VAriance) is used. Next, the mathematical algorithm is exemplified only for the bifactorial variance analysis, but in the study of the vehicle dynamics the generalized MANOVA can be applied, ie the number of factors can be adopted no matter how large. In this sense, it is considered that a number of  $pq$  polls of the same volume  $n$  are randomly extracted from the community  $X$ , subjected to the simultaneous action of two influencing factors A and B. In this case there is the  $x_{ijk}$  matrix of the initial data, with  $i = 1, p, j = 1, q$  și  $k = 1, n$ . It turns out:

- general average:

$$\bar{x}_{...} = \frac{1}{pq} \sum_{i=1}^p \sum_{j=1}^q x_{ij} \tag{7}$$

- general average total variance  $D_t$  and residual variance  $D_r$ :

$$D_t = \frac{\sum_{i=1}^p \sum_{j=1}^q \sum_{k=1}^n (x_{ijk} - \bar{x}_{...})^2}{npq - 1}; D_r = \frac{\sum_{i=1}^p \sum_{j=1}^q \sum_{k=1}^n (x_{ijk} - \bar{x}_{ij})^2}{pq(n - 1)} \tag{8}$$

- the variance related to the interaction between factors A and B (so an interfactorial variance):

$$D_{AB} = \frac{n \sum_{i=1}^p \sum_{j=1}^q (x_{ij} - \bar{x}_{i.} - \bar{x}_{.j} + \bar{x}_{...})^2}{(p - 1)(q - 1)} \tag{9}$$



- the variance related to the influence of factor A and factor B (hence the factorial variance  $D_A$  and  $D_B$ ):

$$D_A = \frac{nq \sum_{i=1}^p (\bar{x}_{i..} - \bar{x}_{...})^2}{p-1}; D_B = \frac{pn \sum_{j=1}^q (\bar{x}_{.j.} - \bar{x}_{...})^2}{q-1} \quad (10)$$

similarly in the case of several influencing factors.

As examples, in fig.5 are presented the results of the variance analysis with the influences of load and engine speed  $n$  (load by accelerator pedal position  $p$ ) on the variation of engine torque  $M_e$ , and in fig.6 on speed Volkswagen Touareg II 3.0 V6 TDI car.

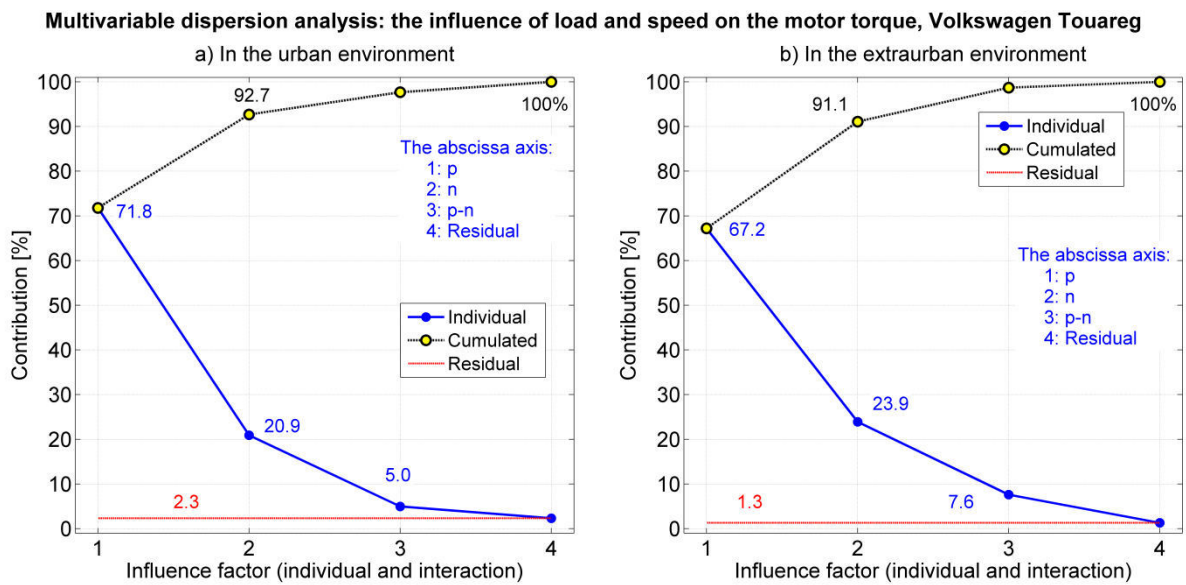


Fig.5. Variance analysis, the influence of engine load and speed on engine torque

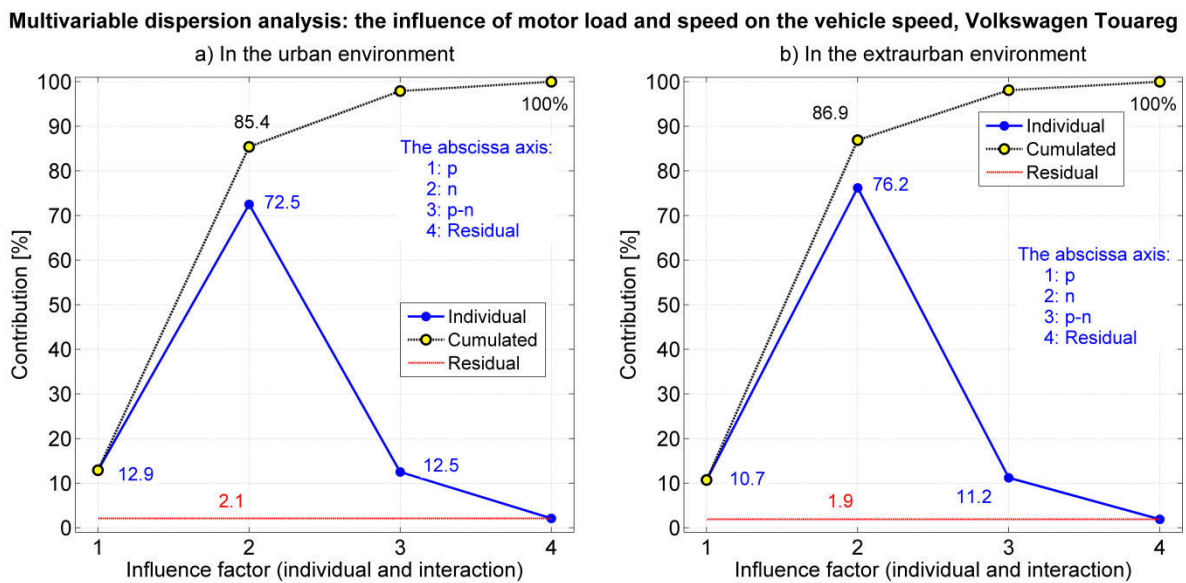


Fig.6. Variance analysis, the influence of engine load and speed on car speed



As can be seen from Fig. 5, the greatest influence on the variation of the motor torque has its load (contribution 71.8% in urban areas and 67.2% in extraurban areas), followed by the influence of speed (contribution 20.9% in urban areas and 23.9% in the extraurban environment). The graphs also show that the mutual influence of load-speed (denoted  $p-n$ ) has a higher contribution than the residual variance (5.0% compared to 2.3%, respectively 7.6% compared to 1.3%) and therefore cannot be neglected.

Instead, from figure 6 it results that the greatest influence on the speed variation has the engine speed (contribution 72.5% in urban area and 76.2% in extraurban environment), followed by the influence of load (contribution 12.9% in urban area and 10.7% in extraurban environment). The graphs also show that the mutual influence load-speed (denoted  $p-n$ ) has a higher contribution than the residual variance (12.5% compared to 2.1%, respectively 11.2% compared to 1.9%) and therefore cannot be neglected.

Fig. 5 and Fig. 6 show the values of the individual contributions to the total variance, as well as the cumulated contributions, whose total amount is 100%.

### V. SENSITIVITY ANALYSIS OF THE VEHICLE DYNAMICS

Also called elasticity, sensitivity expresses the property of a resultant quantity to change its value under the influence of the factorial variable. Similarly to correlation, if there is a single factorial quantity then simple sensitivity is targeted, otherwise it is a multiple sensitivity.

In addition, the local sensitivity is defined, the classical one, which uses the sensitivity function, as well as the global sensitivity, which has as quantitative measure the Sobol index [2].

Finally, the sensitivity may be variable (in which case there is a heterosensitivity) or it may be constant (in which case there is an isosensitivity).

To approach the local sensitivity, a resultant variable  $y$  and a factorial quantity  $x$  are considered. The degree of sensitivity of the resultant variable according to the variation of the factorial quantity is measured using the sensitivity function  $S$ , defined by the ratio between the relative variation of the resultant quantity and the relative variation of the factorial variable, in the considered case:

$$S_x^y = \frac{dy}{y} : \frac{dx}{x} \tag{11}$$

which can also be written as:

$$S_x^y = \frac{x}{y} \frac{dy}{dx} \tag{12}$$

Therefore, if, for example, it is desired to establish the influence of the position of throttle valve  $\xi$  (which defines the engine load) and respectively of the engine speed  $n$  on the travel speed  $V$  (in this case the dynamics of the vehicle is concerned), then the sensitivity functions are established:

$$S_\xi^V = \frac{\xi}{V} \frac{dV}{d\xi}; S_n^V = \frac{n}{V} \frac{dV}{dn} \tag{13}$$

In expressions (13) all quantities are known from experimental data or are calculated on the basis of them (respectively the related derivatives).

The upper graphs in fig. 7 show the instantaneous values of the sensitivity of the travel speed to the variation of the engine speed and the position of the throttle valve, at the 40 tests of the car's movement in the urban environment. The graphs show that there is a functional heterosensitivity (sensitivity function varies over time) for each parameter with other variations over time.

The lower graphs in fig.7 show the average values on samples of the sensitivity function at the 40 tests of the car's movement in the urban environment. As can be seen, the average values on the samples of the sensitivity function are higher in the case of the engine speed than in the engine load (by the position of the throttle valve), including the average on the whole of the tests (0.824 compared to 0.39).

The upper graphs in fig.8 show the instantaneous values of the sensitivity of the travel speed to the variation of the engine speed and of the position of the throttle, at the 40 tests of the car's movement in the extraurban environment. The graphs show that there is a functional heterosensitivity (sensitivity function varies over time) for each parameter with other variations over time.





The lower graphs in fig.8 show the average values on samples of the sensitivity function at the 40 tests of the car's movement in the extraurban environment. As can be seen, the average values on the tests of the sensitivity function are higher for the engine speed than for the engine load (by the position of the throttle valve), including the average for all tests (0.688 compared to 0.339).

The graphs in fig.7 and fig.8 show that in the extraurban environment, the values of the sensitivity function are lower than those in the urban environment. Therefore, in the extraurban environment, the sensitivity of the speed to the variation of the load and the engine speed is lower than that in the urban environment.

**Instantaneous and average values on tests of the sensitivity of the vehicle speed to the variation of the engine speed and engine load, 40 tests in the urban environment, the Logan Laureate car**

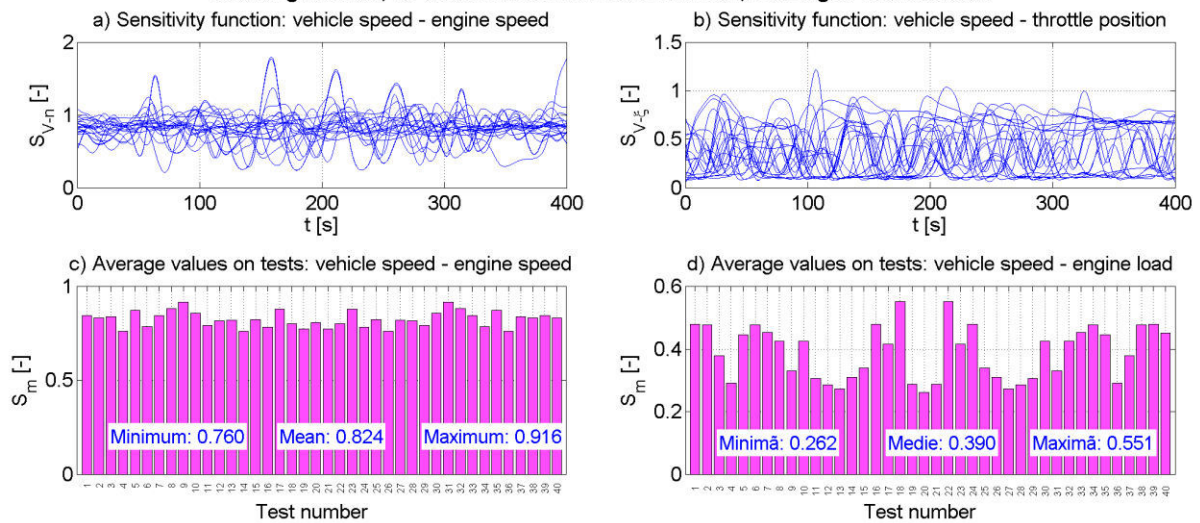


Fig.7. Instantaneous and average values on tests of the speed sensitivity function in the urban environment

**Instantaneous and average values on tests of the sensitivity of the vehicle speed to the variation of the engine speed and engine load, 40 tests in the extraurban environment, the Logan Laureate car**

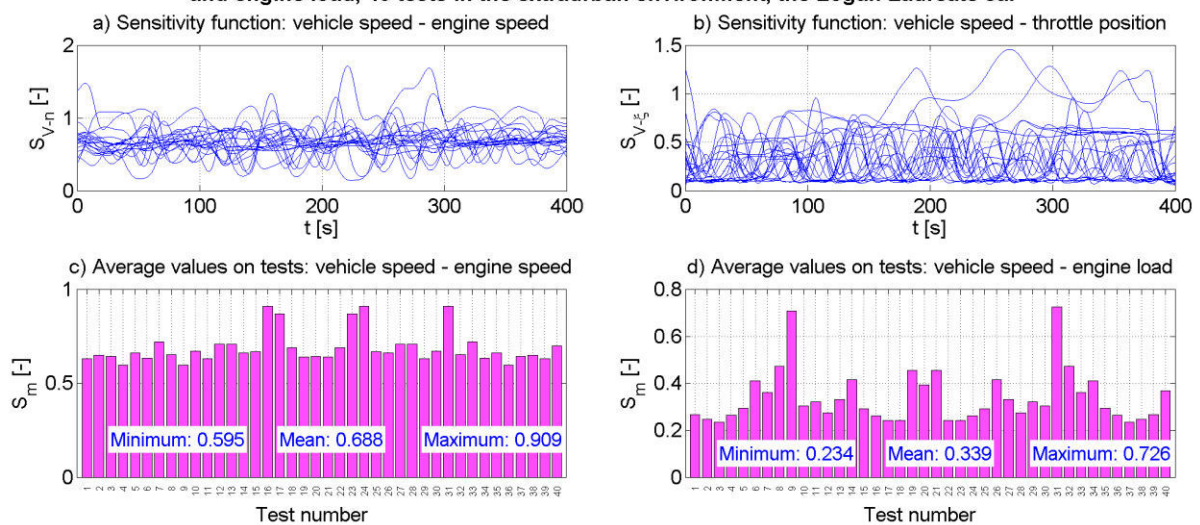


Fig.8. Instantaneous and average values on tests of the speed sensitivity function in the extraurban environment

As mentioned, the global sensitivity has as quantitative measure the Sobol index, denoted by  $S$ . The Sobol index represents the ratio between the variance related to the targeted factor and the total variance of the resulting quantity; as a result, there is the expression [2]:



$$\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \sum_i \sum_{j>i} \sum_{k>j} S_{ijk} + \dots = 1 \tag{14}$$

where for the influence factor  $i$  there is the Sobol  $S_i$  index of order 1 (or the main Sobol index), for the interaction between the factors  $i$  and  $j$  there is the index Sobol  $S_{ij}$  of order 2 etc. As can be seen, the global sensitivity also takes into account the interactions between the factors concerned, similarly to the information analysis and the variance analysis.

As examples, in fig.9 for the urban environment and in fig.10 for the extraurban environment, the first order Sobol index (main) for the engine moment  $M_e$ , the engine power  $P_e$ , the vehicle speed  $V$  and the fuel consumption per 100 km traveled are presented  $C_{100}$  as resultant quantities; the influencing factors are the position of the throttle  $\zeta$ , the engine speed  $n$ , the injection time  $t_i$ , the ignition advance  $\beta$  and the quality of the air-fuel mixture by the excess air coefficient  $\lambda$ .

As can be seen from fig.9 and fig.10, the speed is more influenced by the engine speed compared to the influence of its load (by the position of the throttle), and the influence is lower in the extraurban environment; thus confirming those mentioned at local sensitivity (fig.7 and fig.8).

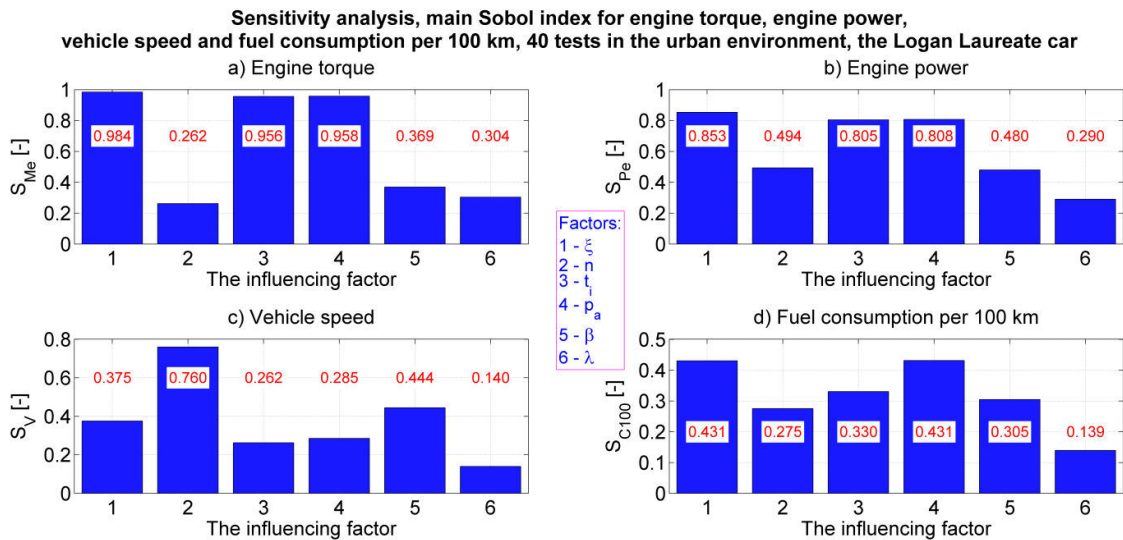


Fig.9. Main Sobol index for four parameters, travel in the urban environment

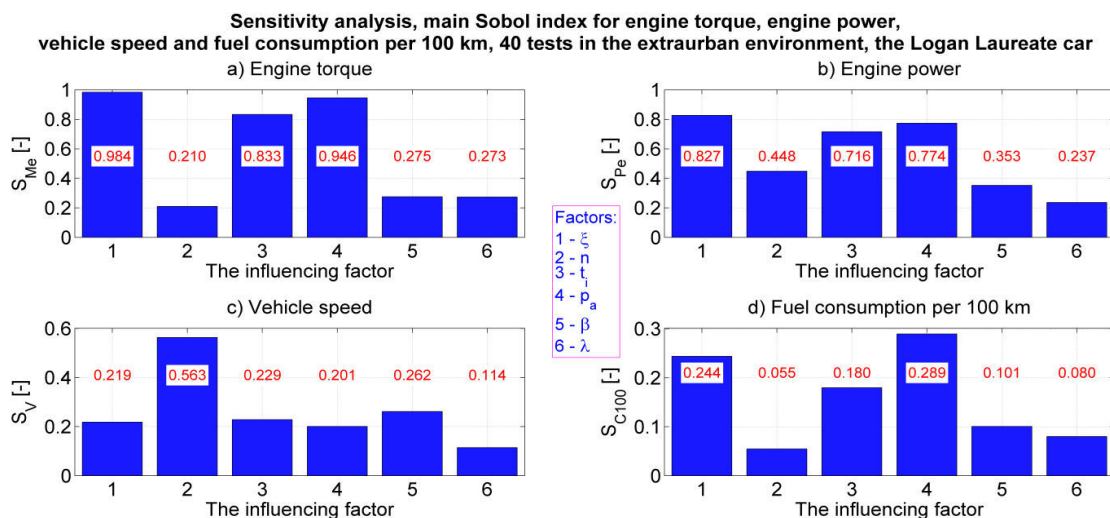


Fig.10. Main Sobol index for four parameters, travel in the extraurban environment



Also, from fig.9 and fig.10 it also results that the torque, power and fuel consumption are more influenced by the engine load than by its speed.

The graphs in fig.9 and fig.10 also show that the first order Sobol index is more or less far from the unit value. According to relation (14), it results that the difference up to the unit value are indices of the second order, three etc., which constitute the interactions between the factorial quantities (influence factors). This again confirms the need to take into account the interactions between influencing factors (functional factors).

## VI. CONCLUSION

The study highlighted which are the functional factors that most influence the performance of vehicles when traveling in urban and extraurban areas.

For the study of the quantitative influence of the functional factors, experimental data obtained from vehicle tests must be used and informational analysis, variance analysis and sensitivity analysis must be used; if the aim is to establish the dependence between the sizes, one can also use the correlation analysis.

Experimental research has shown that during operation, vehicles with dynamic regimes are predominant, and engines run almost all the time at partial loads.

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