The analysis of experimental data obtained from automotives tests

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Abstract. The paper highlights the three important and inseparably aspects of the systemic approach of automotives dynamics: taking into account the human-vehicle-field interaction, dealing movement with algorithms specific to system theory and analysis of experimental data with algorithms specific to signals theory. Within the paper, the systemic approach regarding vehicles dynamics is based on experimental data obtained from tests, whereby it is analyzed the movement and there are obtained movement mathematical models through algorithms of systems identification. Likewise, there are shown main analysis methods for experimental data, which uses probability theory, information theory, correlation analysis and variance analysis; in addition, there are highlighted possibilities given by time analysis, frequency analysis and data time-frequency analysis. Identification algorithms and highlighted analysis procedures assure the study of automotives dynamics and fuel saving, by directly using experimental data, or by using mathematical models and applying concepts and algorithms specific to systems theory. Experimental data were obtained by testing automotives with electronic control devices and by using acquisition and storage equipments for data given by the on-board computer and taken from embedded sensors.

1. Introduction
Vehicles dynamics represents an important and difficult problem, both theoretically and experimentally speaking, that is why it constantly represents interest for experts. The automotives drive on different roadways, whose rolling resistances varies constantly, and the driver frequently intervenes; multiple factors, with complex influence operate on automotives, mostly in presence of different uncertainties.

The study of automotive dynamic response has assumed new possibilities along with the electronic control of it’s functional parameters. The depth of phenomena occurred during functioning can be studied based on information given by the on-board computer, which implies a systemic and interdisciplinary approach of modern automotive dynamics, approach resulted from the structural and adjustment complexity. Regardind those presented, this paper analyses experimental data acquired from embedded sensors and taken by the automotive on-board computer; the analysis of experimental data assures the study of automotives dynamics in real driving conditions[1; 2].

2. Time analysis of experimental data
Time analysis of experimental data allows highlighting the time variation character of different functional parameters, comparisons between different functioning situations and different types of
movement, calculus of statistical characteristics, conclusions regarding the way an electronic control
engine works etc. [1].

So, in figure 1 there are presented two of the most used statistical characteristics, average value $V_m$ (figure 1(a) and figure 1(b)) and maximum value $V_{\text{max}}$ of samples (figure 1(c) and figure 1(d)) for speed in case of 50 start-up samples (figure 1(a) and figure 1(c)) and 50 normal driving samples, named non start-up during the paper (figure 1(b) and figure 1(d)) of Logan Laureate automotive. Figure 1 shows that for start-up, average values and maximum values are higher than for normal driving. Also, it is noticed that in case of start-up, samples variations of average values and maximum values are higher than for non start-up. For example, figure 1(a) shows that for start-up samples, average speeds varies within the range 100.3-112.3 km/h ; instead, figure 1(b) shows that for non start-up samples average speeds varies within the range 41.7-103.4 km/h. Similarly, from lower graphs we can conclude that for start-up samples, maximum speeds varies within the range 137.8-155.1 km/h, and for non start-up varies within the range 66.9-127.6 km/h.

Figure 1 shows throttle shutters position values $\xi$ for the two studied types of movement; in specialty literature, throttle shutter’s position is adopted as a parameter that defines engine load. In this regard, it is reminded that in classical study (theoretical) the automotive start-up is studied with an engine that develops parameters appropriate to exterior characteristic, on full load ($\xi=100\%$), in order to estimate maximal performances [1]. On the other hand, during start-up practical study (in case of running and experiments), the engine runs mostly on partial loads. Indeed, as it can be seen from figure 2, the engine ran on full load only for 0.8% of situations in case of start-up (figure 1(a)) and only for 1.8% in case of non start-up (figure 1(b)); therefore, running on partial loads represents: 99.2% in case of start-up and 98.2% in case of non start-up.

Graphs also show that in case of low and average partial loads, in the range 0-50%, at start-up the engine runs in 7.3% of situations, and at non start-up in 35.7% of cases; likewise, in case of average and high partial loads, in the range 50-100%, at start-up the engine runs in 92.7% of cases, and at non start-up in 64.3% of cases.

![Figure 1. Average and maximum speed values, 50 start-up samples and 50 non start-up samples, Logan Laureate.](image-url)
Engine speed values can be seen from figure 3 and figure 4. So, figure 3(a) shows that in case of start-up 86.4% of values are in the range $n=3000-4500$ rev/min; figure 3(b) shows that in case of non start-up 77.7% of values are in the range $1500-3000$ rev/min, meaning exactly below the range from start-up. Hence, in case of start-up the engine functions mostly at higher engine speeds than the most common values from non start-up.

Looking at engine speeds curves from figure 3(a), we can also observe that in case of start-up, moments of gear shift are explicit, unlike in case of non start-up from figure 3(b).

The highlighting of interval of values in which there are gathered most of the experimental data (in this situation, engine speed) can also be made from the graph of bivariable dependency. One example regarding this is shown in figure 4, where it is presented the dependency between engine torque and...
engine speed; the graph also shows exterior characteristic of engine torque $M_e$ and engine power $P_e$, with a maximum torque obtained at 3000 rev/min.

As it can be seen from figure 4(a), most of the engine torque values in case of start-up are found to the right of maximum torque (90.7%), meaning at higher power, in zone A. Instead, in case of non-start-up from figure 4(b), most of engine torque values are found to the left of maximum torque (86.1%), meaning for lower power values than in case of start-up.

![Figure 4. Exterior characteristics and bivariable distribution of engine speed and engine torque values for start-up (a) and non-start-up (b), Logan Laureate.](image)

### 3. Spectral analysis of experimental data

Spectral analysis of experimental data mainly assures the following\[1\]: to establish frequency spectrum for different functional parameters; to establish harmonic constituent with high energy input from experimental time series, meaning those parts with the highest influence on movement; to establish sampling frequency, including to infer mathematical model sin continuous time (for differential equations); to compare the behavior in frequency domain for different driving situations of vehicle; to establish correlation in frequency domain by applying coherence analysis; to highlight non-linear and unsteady character of automotive behavior in dynamic mode; to establish time arrangement of harmonic constituent with high energy input.

Usually, in specialty literature from automotive field only monospectral frequency analysis is used by applying classical Fourier transform. In this situation there are taken two simplifier inaccurate hypothesis: the automotive is considered to be a linear system and it is made a spectral analysis of experimental time series that are considered to be stationary, so including the time invariable frequency spectrum. In fact, both hypothesis must be excluded, the first one by applying bispectra lanalysis, and the second one by using time-frequency analysis.

Polispectral analysis uses high order statistical moment and consists of time series auto-correlation extension, by using semi-invariants, which represents non-linear combinations of these moments\[1\]. So, bispectral analysis uses the 3rd order semi-invariant, defined by ratio:

$$C_3 (k, r) = M \left\{ y^* [n] y[n + k] y[n + r] \right\}$$  \hspace{1cm} (1)

Where $M\{\cdot\}$ represents the statistical mediation operator, mark "*" represents the complex-conjugate of certain discrete time series $y[n]$ known from experiments, and $k \in (-\infty, \infty)$, $r \in (-\infty, \infty)$. Reductively, the
bispectrum of time series $y[n]$ is:

$$S_{yy}(v_1, v_2) = \sum_k \sum_r C_{yy}(k, r) e^{-j2\pi v_1 k} e^{-j2\pi v_2 r}$$  \hspace{1cm} (2)

Bispectral frequency analysis is used to highlight non-linear character of automotives dynamics, meaning to highlight non-linear constituent from experimental series. For example, figure 5 shows the results of engine power bispectral analysis in case of start-up sample LD29 of Logan Laureate automotive. In part (a) is represented the engine power, in part (b) is represented the third order cumulant in kW$^3$, in part (c) is represented the bispectral amplitude in kW$^3$/Hz$^2$ and in part (d) is represented the bispectral phase in degrees. In these graphs, frequency bandwidth $\nu_1$ is assigned to linear constituent, and frequency bandwidth $\nu_2$ is associated with non-linear constituent; similarly, times $\tau_1$ and $\tau_2$ from figure 5(b). The graphs presented underline the existence in experimental time serie of a non-linear constituent; if there was not a non-linear constituent, then graphs from figure 5(b), figure 5(c) and figure 5(d) would not contain images.

Similarly, a bispectral analysis is made for any functional parameter that defines automotives dynamics and fuel saving or it’s engine performances. Bispectral analyses that were made regarding all experimental data confirmed that all functional parameters also contain a non-linear constituent, of a higher value than the linear one, with implications in establishing mathematical models for automotives dynamics (these must be mostly non-linear).

Figure 5. Bispectral analysis of engine power, start-up sample LD29, Logan Laureate.

Most commonly used time-frequency analysis techniques are [1]: non-transform representations: spectogram, sonogram, vibro-record, scalogram, periodogram; linear transforms: short-time Fourier transform; bilinear transforms of Cohen class: Wigner-Ville, Gabor, Zak, Choi-Williams, Zao-Atlas-Mark, Born-Jordan, Page-Levin, Bertrand, Flandrin, Rihaczek, Margenau-Hill, Bud etc.; wavelet transforms: Haar, Morlet, Gabor etc.; multiresolution analysis methods: Daubechies, Symmlet, Vaidyanathan, Haar, Cojiletetc; S transform, proposed by Stockwell.

For example, figure 6 presents results of time-frequency analysis by applying Stockwell transform to the experimental time serie of engine speed in case of start-up sample LD15 and non start-up sample LN15 (in part (a) is presented the transform amplitude for start-up, in part (b) is presented the Stockwell transform for start-up, in part (c) is presented the transform amplitude for non start-up and in part (d) is presented the Stockwell transform for non start-up).
Figure 6. Time-frequency analysis of engine speed, Stockwell transform, LD15 and LN1 samples, Logan Laureate.

Graphical combination shown in figure 6 allows a more clearly highlight of areas where energy input of harmonic constituents is high. For example, from upper graphs (at start-up) is determined that the highest energy density is around the moment $t=5$ s (figure 6(b)), when it is reached the maximum of Stockwell transform amplitude $A(1.1; 390)$ from figure 6(a), associated with 1.1 Hz frequency. Similarly, from lower graphs (at non start-up) is determined that the highest energy density is in the time range $t=21-34$ s (figure 6(d)), when it is reached the maximum of Stockwell transform amplitude $B(2.5; 450)$ from figure 6(c), associated with 2.5 Hz frequency.

4. Conclusion
The study based on experimental data of automotives dynamics equipped with on-board computer, allows a practical approach of it’s movement in actual conditions of usage.

5. References
[1] Copae I, Lespezeanu I and Cazacu C 2006 Dinamica autovehiculelor (Bucharest: ERICOM Publishing company)
[2] Gray R 2007 Entropy and information theory (New York: Stanford University)