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NEW ASPECTS REGARDING CONTROL AND OPERATION OF THE AUTOCAR ABS SYSTEM

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Abstract. *The study embraced theoretical and experimental aspects related to the functioning of the vehicle ABS system. We evidentiated new strategies and algorithms of ABS control and a spectral analysis of the ABS operation, consisting of frequency and time-frequency analysis. Moreover, experimental data emphasizes the influence of factors on the functioning ABS by calling the sensitivity, dispersional and informational analysis.*
Keywords*: autocar, ABS system, electronic control, time-frequency analysis*

1. INTRODUCTION

More severe requirements imposed on automobile power performance, economy and emissions were added and active safety requirements for passenger, cargo and road traffic. The most advanced active safety systems fitted to existing vehicles, such as ESC and ESP, ABS system based on the best known and most used electronic control system. For this reason, this study addresses the issue of ABS operation when driving the car on different runways and using different control algorithms.

2. MODELING OF OPERATION AND CONTROL ABS

Modeling ABS operation has two large components [6]: mathematical algorithm of vehicle dynamics during braking and control law (size control). The paper is illustrated only well-known model in the literature as "quarter-vehicle", also called *the model with a wheel*. For this model, the equations of motion of the car during braking, considering that it moves horizontally on a runway and neglecting the aerodynamic- and rolling resistance, are:

$$\begin{cases} m\dot{v} = -F_x \\ J\dot{\mu}_r = rF_x - M_f \end{cases} \tag{1}$$

where: m-mass of the vehicle, v-longitudinal speed of the car, F_x–adherence strength, J-moment of inertia of the wheel, μ_r-angular speed of the wheel, r -radius of the wheel, M_f -braking moment. From their appearance and to date, the ABS systems have benefited from control strategies and control algorithms depending on the technological level of the three major components: sensors, actuators and onboard computer. Thus, initially the control system was based on braking pressure modulation algorithm coupled/decoupled (*on/off system* so-called *bang-bang control*) following ***the control the wheel deceleration***; over time the control was exquisite, relying today on artificial intelligence algorithms in order to control ***the wheel slipping and the mixed control system (slip and deceleration)***. Among the most commonly used control algorithms are: control with feedback loop, bang-bang control (signum), PID control (proportional-integral-derivative), adaptive control, control based on artificial intelligence algorithms (based on fuzzy logic, based on neural network, neuro-fuzzy, based on genetic algorithms), robust control etc. For example, bang-bang control has the mathematical description [6]:

$$u(t) = \begin{cases} 1, \text{ dacă } £(t) > 0 \\ 0, \text{ dacă } £(t) = 0 \\ -1, \text{ dacă } £(t) < 0 \end{cases} ; \; £(t) = ª_i - ª(t) \tag{2}$$

where, *u(t)*-size of the command (control law), *e(t)* – error and the last size $ª_i$ - represents the difference between slipping imposed to ABS system (usually, $ª_i$=0.20 which wheel-ground adherence is maximized) and ª real wheel slippage.

3. SIMULATION OF THE ABS SYSTEM

For simulation of ABS system is used its own software *Matlab* and *Simulink Toolbox*. This simulation allows pointing some functional features when car is moving on different runways and using some practical control algorithms.

In Figure 1 is shown the values of v -vehicle speed, v_r-wheel peripheral speed and u -command size (control law) ***when traveling on wet pavement*** using ***bang-bang controller for ABS***, for ABS providing condition to ensure an imposed longitudinal sliding coefficient λ_i=0.20 properly corresponding to maximum adhesion coefficient ¨ $_{max}$ =0.45 for wet asphalt.

Furthermore, Figure1a reveals that the initial speed of ABS system operation was v_0 =25 m/s (90 km/h). Likewise, it is observed the existence of an oscillatory feature of the wheel curve with v_r–wheel peripheral speed, leading to ***the need of analyzing the ABS function frequency***. ***In addition, as the frequency increases and amplitude decreases towards the end of braking is required a time-frequency analysis*** of the functioning ABS, too. In the graph are shown the values of the braking time t_f =6.19s and the final velocity of the vehicle and v_f =1.3 m/s. Also, as noted, the wheel peripheral speed v_r is always lower than that of the vehicle v, obviously due to slippage issue also valid to the mean value v_{mr} compared to v_m.

In Figure1b reflects u -size control presented in expressions (2), which is the bang-bang control law; the chart is shown as continuous representation (commonly used, but unreal) and discrete representation (rarely used, but real). From the graph it appears that the size control has the values +1 and -1but not zero. We also notice that the frequency command increases in size over time.

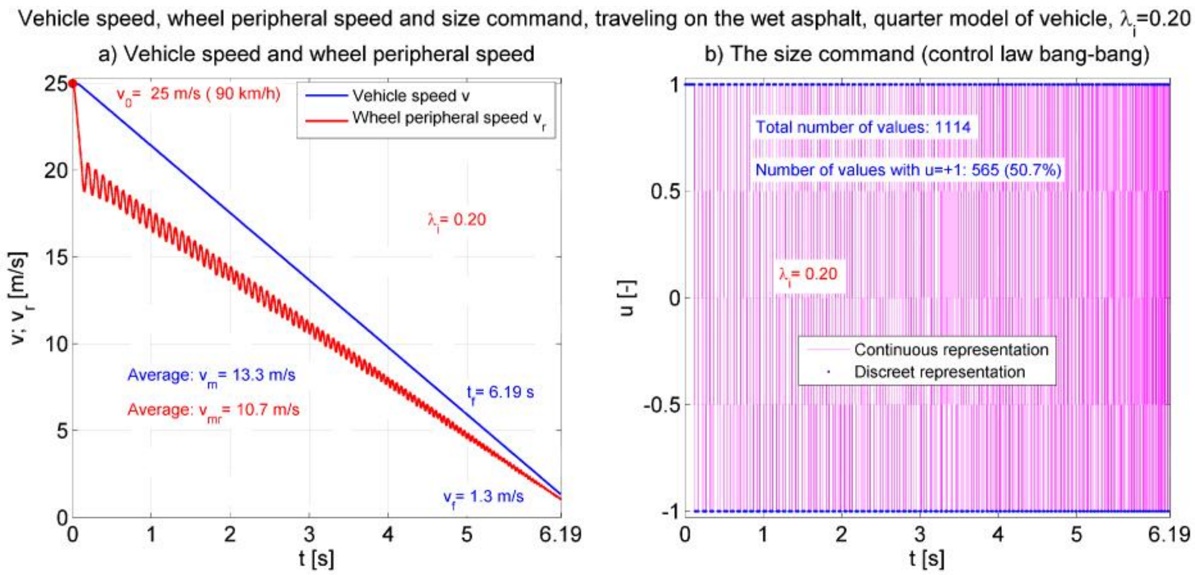

Figure 1. Representation of vehicle speed, wheel peripheral speed and size command

Figure 2 shows the adhesion coefficient values ¨ and braking space S_f for sliding imposed to the system ª$_i$=0.20. The graph from Figure 2a reveals that adherence coefficient ¨ is not always strictly related slip imposed ªi, but most of the values are around it. Thus, the graph shows that 98% of the adherence coefficient is in the range of 0.40-0.45 lying around ªi=0.20 related slip. Also, the graph reveals that the mean value of the adhesion coefficient is 0.43.

Figure 2b develops that the value of braking space is S_f =82.3 m. The right-hand chart shown the value of the wheel equivalent space S_r, which is smaller than that braking space S_f, obviously because of slipping, and thereby situating the curve wheel peripheral speed v_r under the curve car speed v (Figure 1); such as, from Figure 2b can be deduced that wheel slipped 19.7% from total area covered, and 80.3% of it performed a normal running.

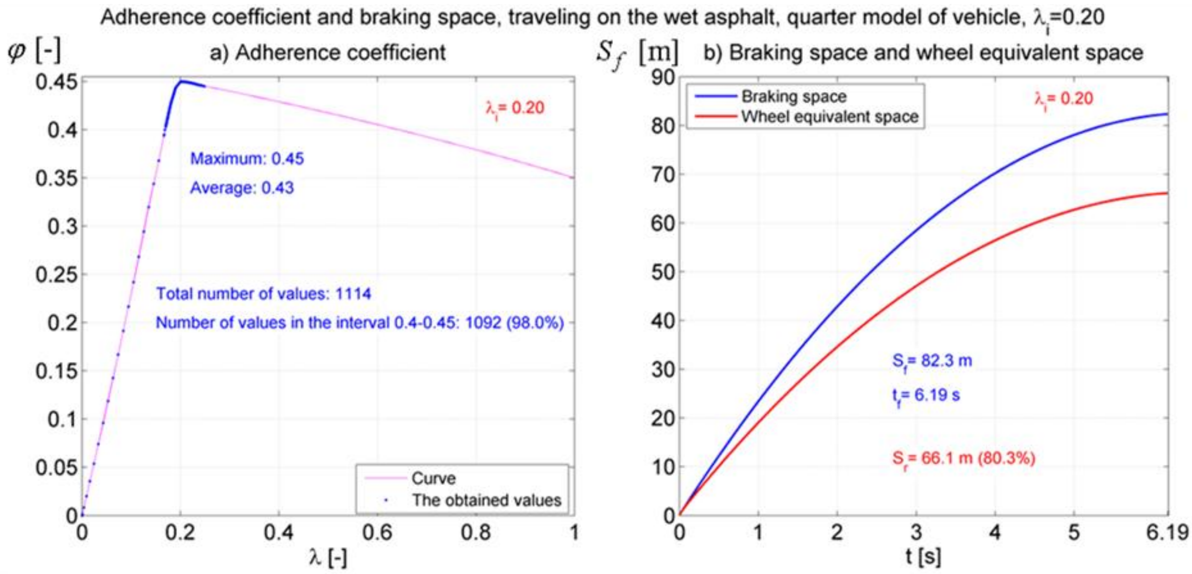

Figure 2. The adherence coefficient and braking space

Similarly can be exemplified other cases on different driveways with different control algorithms and different slip values imposed to ABS system, ª$_i$ (e.g. ª$_i$=0.15 and ª$_i$=0.25). Studies done in this regard permit to deduce the following conclusions: with increasing slip imposed the oscillatory character of the wheel movement is change: decrease the frequency and increase the amplitude of the oscillations. Therefore, with increased of the slipping imposed rises the difference between the car mean speed v_m and wheel mean speed peripheral $v_{mr,}$ so the two curves from Figure1a drive away. So, the minimum of the braking time and the braking space related to the slip ª$_i$=0.2 permits a maximum of the adhesion coefficient. It has been observed that as increasing imposed slip decreases othe wheel equivalent space, S_r. Since slipping imposed is higher, the variation rate of command size is smaller (switching from one discrete value to another beeing uncommon); braking time and - space grow on driveways with reduced adhesion, for example on ice in comparison with braking on the wet pavement. Accordingly, using PID controller or fuzzy PD controller, the braking-time increases and decreases braking-space comparing if used controller Signum (bang-bang), but the differences are reduced.

4. SPECTRUM ANALYSIS OF ABS OPERATION SYSTEM

From the above has shown that during braking process with ABS operation occur oscillatory processes with different frequencies and amplitudes of measurements such as the wheels peripheral speed (as well as the angular speed), the braking moment, the braking pressure, the friction coefficient, the coefficient of sliding etc. Therefore, it is necessary a spectral analysis of the ABS operation, as well as a frequency analysis and time-frequency analysis of it [2].

Frequency analysis of the functioning ABS system appeal to classical Fourier transform, which ensure emphasizing of the harmonic components with high energy intake among dynamic series. Instead, *time-frequency analysis* of the ABS operation enables time positioning of the various harmonic components, including those with high energy intake. This analysis uses the Class Cohen transform (Wigner-Ville, Gabor, Zak, Choi-Williams, Zao-Atlas-Mark, Born-Jordan, Page-Levin etc.), the wavelet transform, the Stockwell transform etc. [2].

Figure 3a illustrates the frequency analysis, and in Figure 3b the time-frequency analysis of the ABS operation, the target being the wheel peripheral speed when driving on wet asphalt with ª*i* =0.2 given above in Figure 1a. As expected from these graphs, only time-frequency analysis can detect the disposition in time of the harmonic components, including those with high energy intake (Figure 3c).
Indeed, as seen in Figure 3b, the highest energy intake is bring the harmonics with frequency around 6.1 Hz acting at time moments of around 0.35 seconds.However, the graph from Figure 3b confirms that *wheel oscillations are reduced in amplitude and increase in frequency towards the end of braking.*

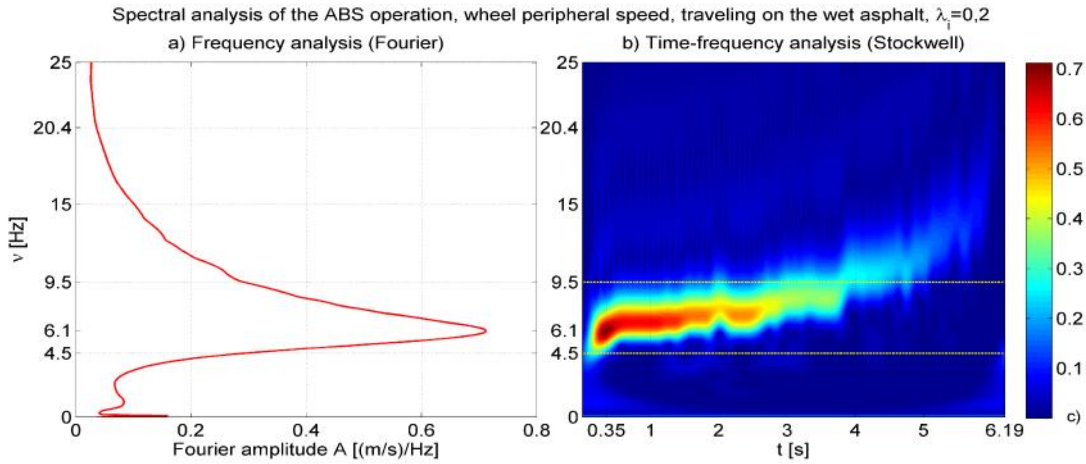

Figure. 3. Spectral analysis of the ABS operation

Also, from Figure 3 is reaveling *the harmonics frequency spectrum as well having the highest energy contribution* of 4.5-9.5 Hz for the analyzed case of the wheel peripheral speed.

5. INFLUENCE OF CERTAIN FACTORS ON THE ABS OPERATION

ABS operation is influenced by many factors that affect its performance, the main including braking time and braking space of vehicles [3; 6]. To determine the influence of those functional factors on the performance of ABS operation, the main methods used in practice are sensitivity analysis, informational analysis and dispersion analysis. Those methods set quantitative influence on the ABS functioning [1; 2; 4; 5]. *The sensitivity* expresses a property of a resultative size in order to modify its values under the influence of factorial size and influence factor, respectively [4]. Among the indicators that quantify sensitivity is Sobol's index noted by *S* and represents the ratio between afferent dispersion of the targeted factor and the total dispersion of the outcome size. As an example, Figure 4 shows the Order I Sobol's index for braking space S_f and braking time t_f (two resultative sizes) when driving on wet asphalt with Signum controller, the six influence factors being (x-axis) 1. ¨ -adhesion coefficient; 2. ª -slipping coefficient; 3. *u*–command size ; 4. v_r–wheel peripheral speed; 5. *v* –vehicle speed; 6. M_f-braking moment.

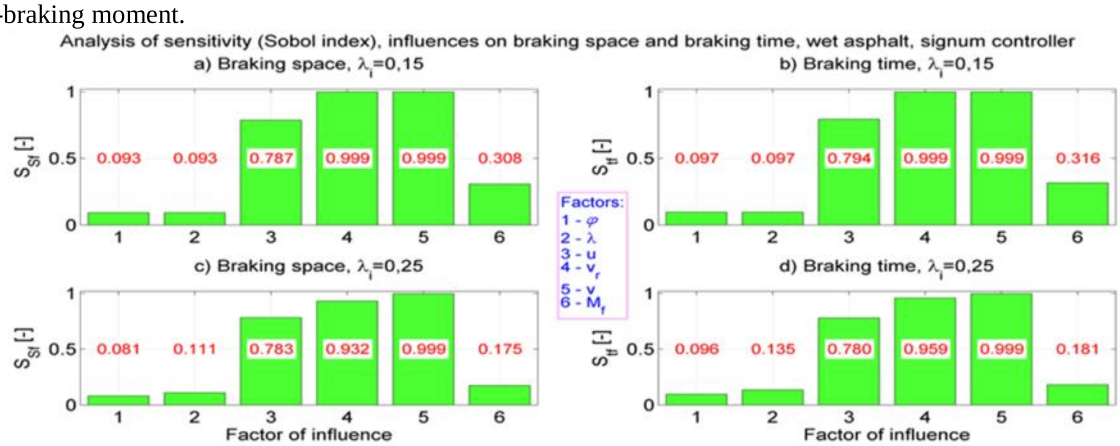

Figure 4. Analysis of Sensitivity

As expected from these graphs, braking time and braking space are the most sensitive to changes in peripheral speed of the wheel, v_r and the vehicle's speed, v (expected), followed by size *u*-command size and at a greater distance for braking moment, M_f. In addition, the lowest influences show ¨ -adhesion coefficient and ª-slipping coefficient. Also, these graphs reveal that the mentioned influences are apparent both at low values of slip coefficient imposed $ª_i$=0.15, at the left peak of the curve ¨ $= f(ª)$ with λ=0.2, and at higher values of it ª*i*=0.25, at the right peak of the curve ¨ $= f(ª)$. It should be noted that when braking moment but is more the slipping coefficient imposed λi=0.15.

Informational analysis is based on two main concepts of informational theory: entropy and information, including mutual information [5]. Mutual information is a concept that provides a quantitative measure to minimize uncertainty, so to increase the prediction. The more the mutual information gain higher values, the smaller uncertainties will become and therefore higher predictions. For this reason, mutual information is a basic concept for the study of the dynamics of the systems and *is a measure of the interdependence of the variables*.

As an example, in the chart from Figure 5 is shown the results of the informational analysis when consider the braking space a resultative size (placed at the top) and taking into account the 6 factorial sizes (determinants) such as: the adhesion coefficient, the slipping coefficient, the size command, the wheel peripheral speed, the vehicle speed and the braking moment. The nodes of the graph are given entropy values, *H*. It appears that most entropy is possess by braking space of *H*=4.4 bits, and the smallest size command of *H*=2.6 bits. On the graphic curves are noted the mutual information values *I* between two sizes.

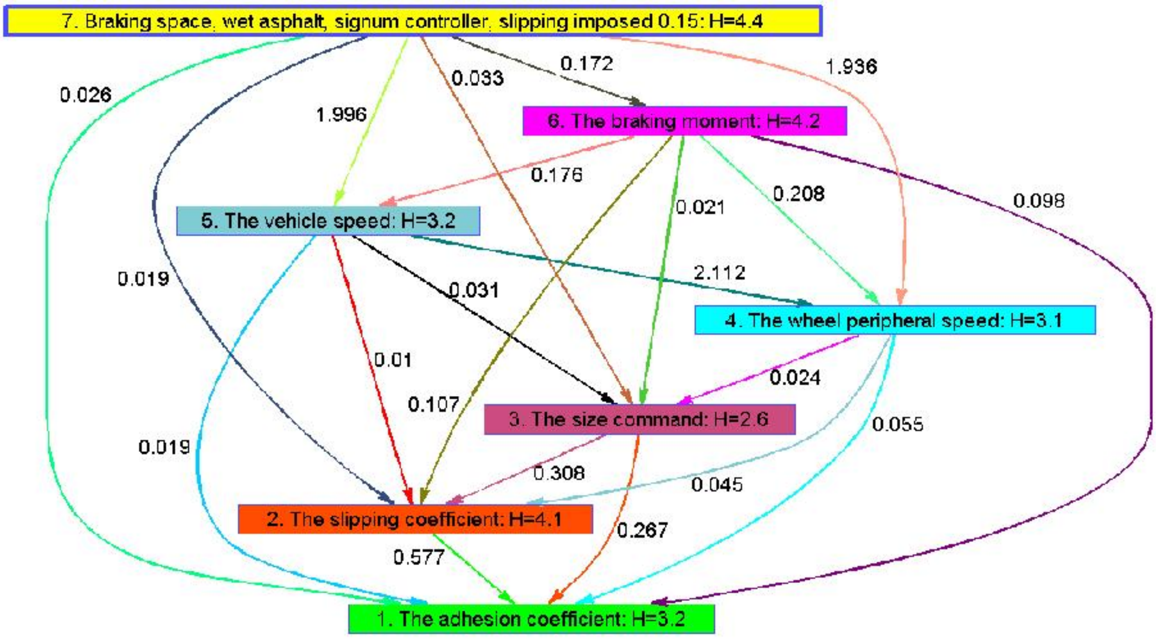

Figure 5. Informational analysis

From Figure 5 it is noted that the first two relevant variables (with the greatest influence on the braking-space) are the car speed (mutual information with braking space of 1.996 bits) and the peripheral speed of the wheel (*I*=1,936 bits), same as the sensitivity analysis (Figure 4a, with ª*i* =0.15).

6. EXPERIMENTAL RESEARCH

To perform the experimental study on the ABS operation were performed some tests with recording the speed of movement and the wheel speed revving to both types of car, Skoda Octavia and BMW 523i. Acquisition and data storage was possible because of the existence of embedded sensors, a board computer, a specialized tester and an embedded computer with specialized software. The data were processed subsequently purchased a computer and appropriate software.Figure 6 shows the experimental results of the braking time t_f, the braking space S_f, initial speed V_0 and the final speed V_f when the vehicle Skoda Octavia was 15 times tested by *driving on wet asphalt* and in Figure 7 the analytical afferent expressions offering functional dependencies of the first three sizes.

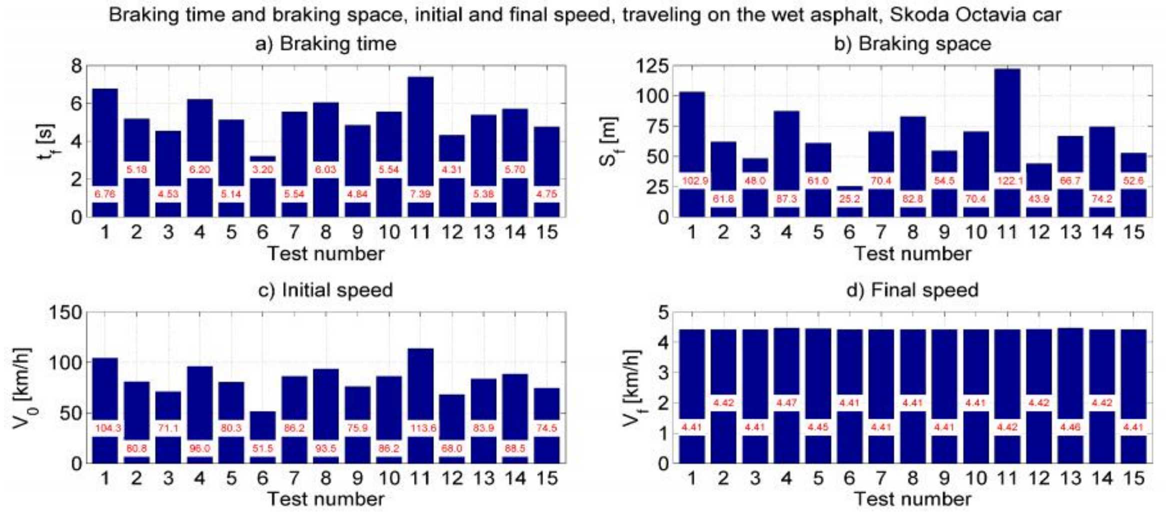

Figure 6. Sizes defining the braking process

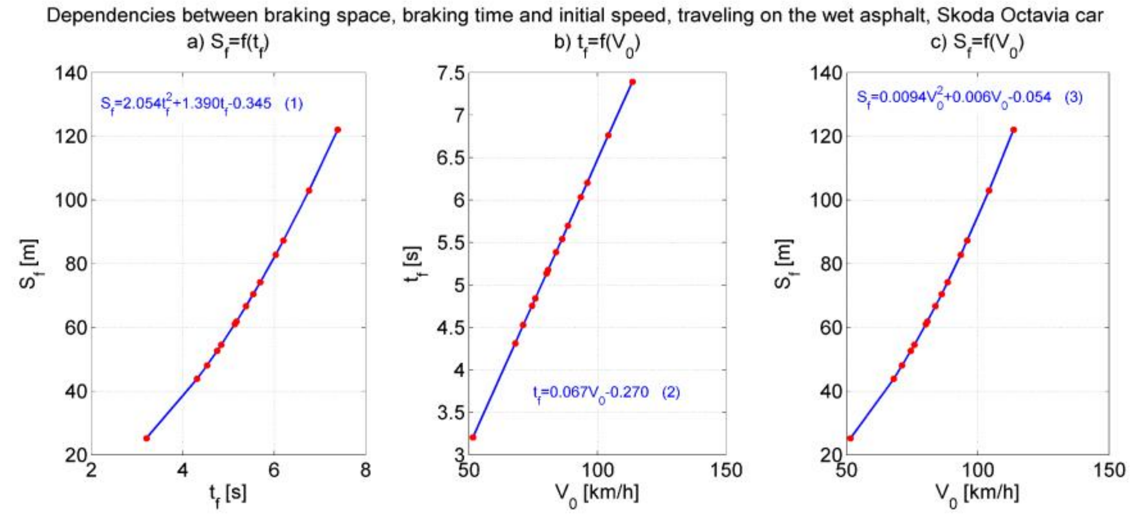

Figure 7. Functional dependencies between brake sizes

As shown in Figure 6, the braking time varied in the range from t_f =3.2-7.39 s and braking space S_f = 25.2-122.1 m, the initial speed V_0 =51,5-113,6 km/h and final speed V_f =4.41-4.47 km/h.

7. CONCLUSIONS

To study the ABS operation based on experimental data allows emphasizing some specific features that resort to methods and specific algorithms for systems dynamics. It follows that the influence of various factors on the ABS operation must be consider and the interactions between factors as well as that of the factorial sizes vary simultaneously during operation, two main differences to the study of classical literature.

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