

# The estimation of friction coefficient of brake pad- disc during braking process in different operating conditions

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**Abstract.** In the paper, the results of the research were discussed, the aim of which was the estimation of the friction coefficient of brake pad- brake disc during braking a vehicle with regard to the influence of external conditions. B Segment vehicle with independent suspension was used for measurement and tests. Test brakes were made on the drum test stand the moment of inertia of which was chosen so that kinetic energy lost during the test would be the same as during road tests. The step of wetting of the brake disc and pads was taken into consideration during the research. The research was conducted comparatively for the vehicle with acting anti-lock braking system and subsequently for the vehicle without the system. The friction materials used in disc brake systems are required to provide a stable friction coefficient. From the point of view of efficiency of operation the brake system, the characteristics of the variation of friction coefficient of the brake disc and pads have a special meaning. Neural network was applied to estimate the value of friction coefficient during braking. The results obtained during the measurements were compared to the estimated values.

## 1. Introduction

Disc brake systems have been prevalent in passenger vehicles since the 1960s and are used more extensively in modern vehicles. The friction materials used in disc brake systems are required to provide a stable friction coefficient, and low wear rate at various operating conditions. Friction material must also be compatible with the rotor material in order to reduce its extensive wear during braking. All of these requirements need to be achieved at a reasonable cost and minimum environmental load. The brake pad properties have essential meaning in automotive brake system and influence on the effectiveness of braking. The demand for these elements concerns value and stability of the coefficient of friction as well as the durability of the friction linings. From the point of view of efficiency of operation, the characteristics of the friction coefficient in the function of unit pressure, relative speed of the friction pair and temperature as well as the step of wetting of the brake disc and pads have a special meaning. The tribological investigation has shown considerably differences in the value and course of the coefficient of friction depending on temperature and time of braking for materials used for brake pads [1,4,6]

Investigation of topography, chemical properties and wear of the friction layer of pads and discs are undertaken by many research and industrial centres [2,3,4,5,6,7]. Necessity of the investigation in this domain results from new regulations, from growth of the energy and power of braking and from ecological demands [6,8]. The investigation in this area has special meaning because of influence of

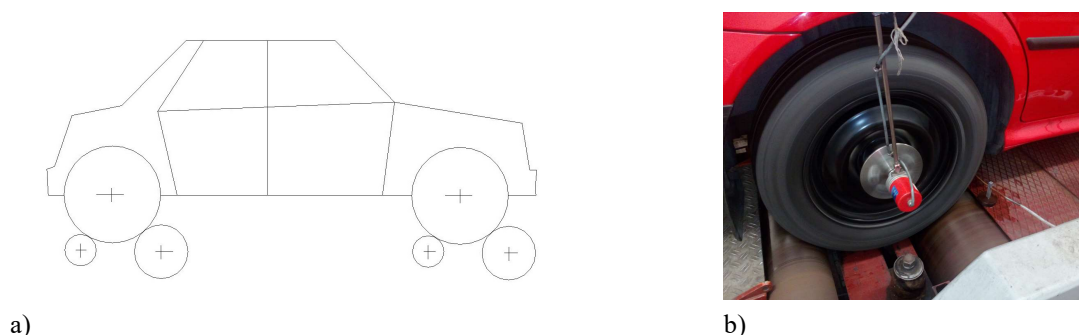


operation conditions of friction pairs on stability of the brake mechanism. It is also essential due to the possibility of foreseeing the friction characteristic of frictional materials [9,10]. Composition of frictional materials changes: from prohibition of the use asbestos, next gradually elimination of the heavy metals, up to elimination of the copper – one of the important components of brake pads [2,3,5,11]. Due to the place where it is assembled, brake disc is exposed to the impact of external factors. This results in the sensitivity of torque effectiveness to the presence of various contamination the disc surface. Water during a ride in rainy weather can be one of such factors. At the same time, the change of friction coefficient of brake pads and brake disc during braking may have an influence on the braking effectiveness. Simultaneously, brake system control has an influence on vehicle's stability and steerability [1,13,14,15,16].

The aim of the research was to estimate the value of friction coefficient in pair of brake pads and brake disk during vehicle's braking maneuver with regard to the influence of external conditions.

## 2. Experimental procedure

A special test stand was used to do the research. It enables placing the whole vehicle on rotary drums. Each wheel of the vehicle is supported by two drums. They can be scorched to a proper velocity by electrical motors. After the achievement of the assumed velocity, the motors become disconnected from the drums by clutches. At that time, braking of the vehicle can be started. Each of the test stand drums is joined to the steel pulley. The steel pulley has the moment of inertia adjusted in such manner that the vehicle kinetic energy lost while braking on the test stand must be equal to the energy lost during braking on the road. The large tyre-road surface contact generates the slip and on the basis of the drum rotational velocity, the vehicle linear velocity can be calculated. A simplified scheme of the test stand and the drums under the wheel of the vehicle were shown in figure 1. An exact description of the test stand was placed in the publication [17]. All tests were conducted on the vehicle – B Segment in Euro Market Segment car classification with independent suspension. On the front, the vehicle was equipped with multi-link suspension, whereas at the back of the vehicle – trailing-arm suspension. Telescopic shock absorbers were installed both on the front and at the back. The rotational speed of the vehicle wheels and drums was measured with tachometric generators. In hydraulic circuit of vehicle brake system, pressure sensors were assembled. Measurement sensors were connected to an analog-to digital converter produced by Hottinger Baldwin Messtechnik GmbH.



**Figure 1.** The test stand for the braking test; a) – a simplified scheme of the stand , b) – the wheel of the vehicle on the drums

With the aim of determining current value of friction coefficient between brake pad and brake disc, model of a wheel operating in transient state described in the paper [18] was used. The braked wheel rotates with the angular velocity  $\Omega(t)$ , which changes according to the applied braking torque

$M_b(t)$ . The static wheel radius is described by  $R_l$ . The force tangential to the road ( $F_x$ ) is described as the product of longitudinal slip stiffness ( $C_\kappa$ ) and the longitudinal slip at the tyre-road contact  $\kappa'$ . The linear velocity  $V(t)$  corresponds to the vehicle body with mass  $m$ . The wheel rotational direction equilibrium is described by the following equation:

$$J_{wheel} \cdot \dot{\Omega} = -R_l \cdot C_\kappa \cdot \kappa' - M_b \approx -R_e \cdot C_\kappa \cdot \kappa' - M_b \quad (1)$$

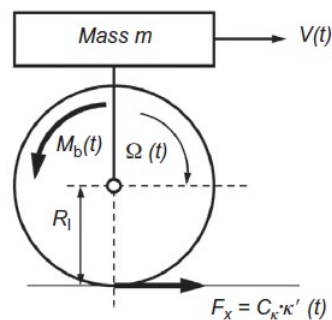
The model parameters, including the wheel moment of inertia ( $J_{wheel}$ ), are involved with the front axle and braking system parameters of test vehicle. The effective tyre radius ( $R_e$ ) is the distance between the wheel center and the real contact point between the tyre and the road. It was calculated on the basis of the wheel dynamic load [18]. The braking torque can be calculated as follows:

$$M_b = P_p \cdot \mu \cdot R_p \quad (2)$$

$\mu$  - friction coefficient of brake pad and brake disc;

$R_p$  - the distance between the centre of the brake pad and the wheel centre.

In figure 2 forces and torques operating on the wheel during the braking process were shown. In the analyses, changes of normal forces between the tire and the road resulting from a given maneuver was taken into account. For calculations, parameters of size were adopted which corresponded to those of the tested car.



**Figure 2.** The main parameters of the wheel during the braking process [18]

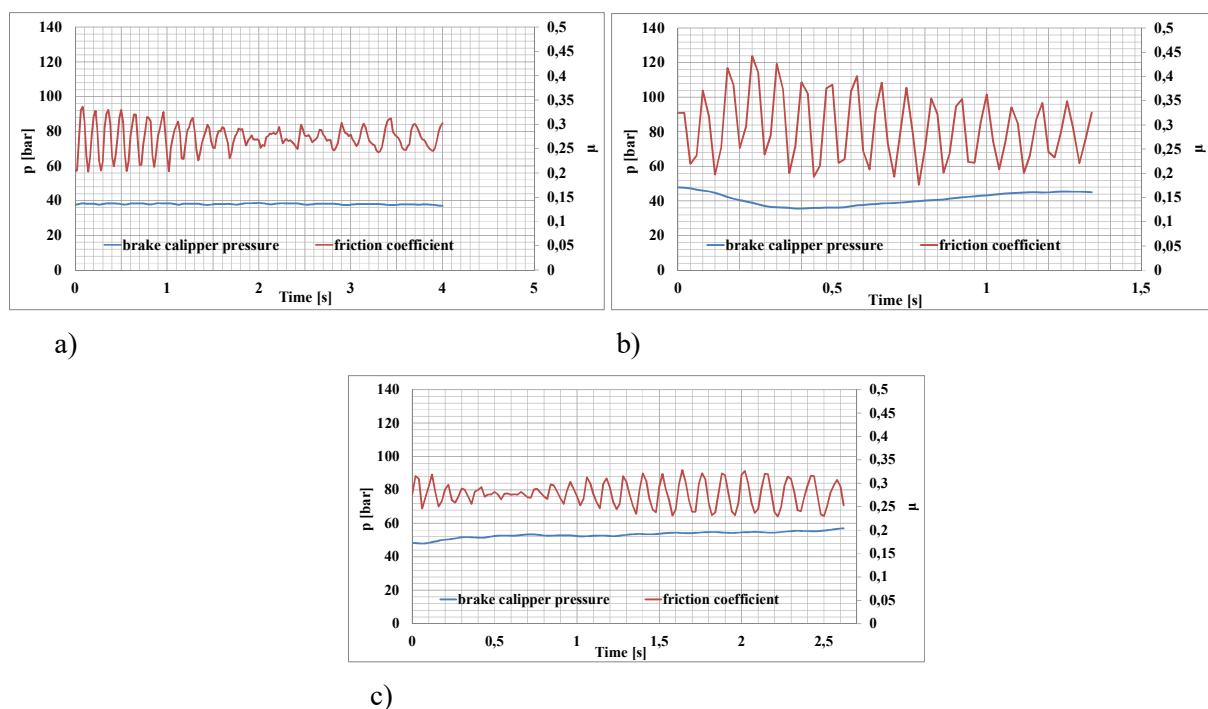
### 3. Neural network

Artificial neural networks are those categories of dynamical systems that transmit hidden knowledge or rule behind the data to the network structure by processing the experimental data. Their abilities to learn patterns and relations among data are similar to the human's ability of learning from experience. Neural networks are composed of a set of simple and adaptive processing units, called neurons. Each neuron receives signals from the input through interconnections. The connecting links associated with adjustable values are called weights. Inputs are multiplied by assigning a different weight to each of them. In fact, the weights specify the intensity of an input signal and help neural network to solve the problem. Another parameter of the neuron which can be modified is called so bias. It is added to the summation of products. At the end, an output is obtained through an activation function which generates a limited result. A typical multilayer feed-forward neural network or multilayer perceptron consists of a certain number of neurons arranged in the following layers: an input layer, output layer, and hidden layer of neurons. Such networks can be applied to approximate almost any function. With the aim of solving more complex tasks, the hidden layer must contain sufficient number of neurons [19]. The main idea is to build an intelligent nonlinear system by means of a multilayer perceptron neural network which makes the correspondence between output and input data like a mathematical function.

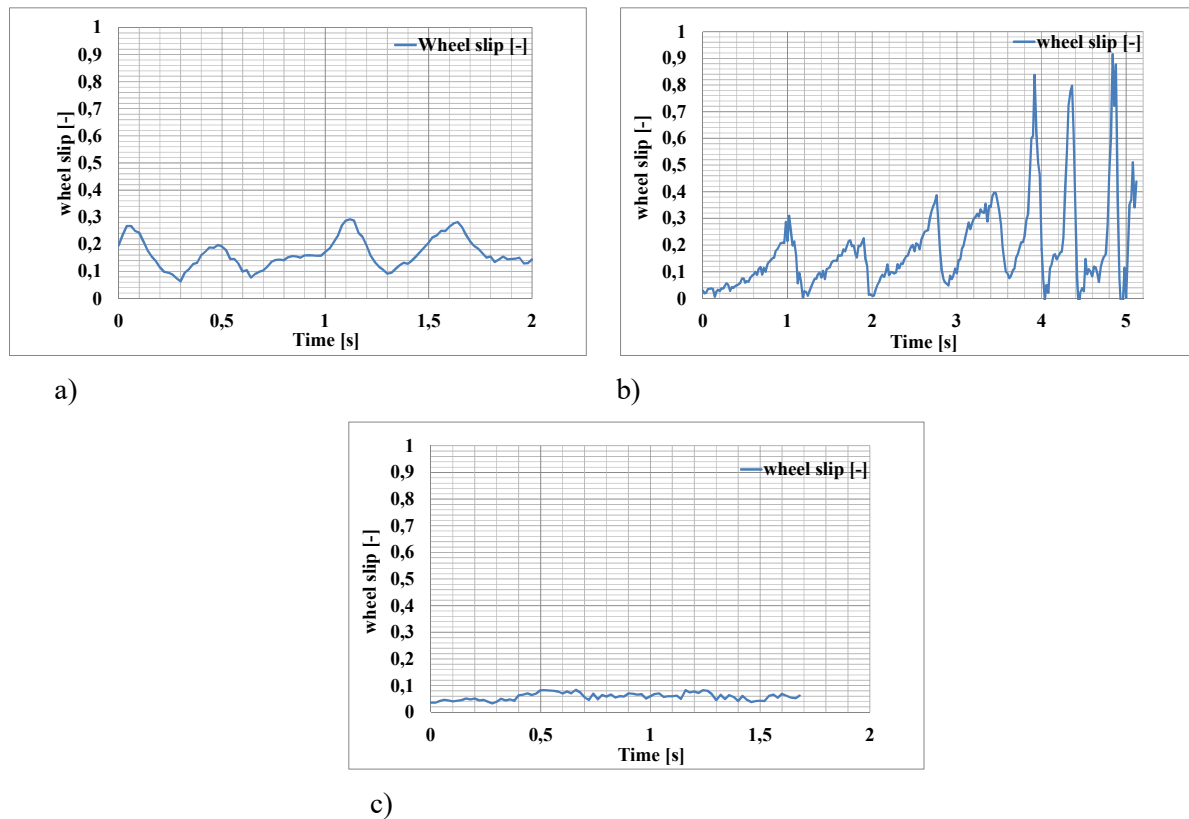
Based on measured data, an artificial neural network was built the aim of which was to estimate friction coefficient on the basis of variable operating conditions. Designing of the neural network consists of three stages of data collecting, data training, and data testing. To avoid complexity of neural network rule extraction, the range of the input data and subsequently output data are limited. The neural network, used for the friction coefficient estimation was formulated as a two-layer-feed-forward network with 10 sigmoid hidden neurons and output layer linear neurons. As a result of the data collection process, matrices 2x524 of data was obtained. Then, the matrices were divided into training and test sets and were used to train a neural network. For calculations the MATLAB numerical computing environment was used.

#### 4. Results of research

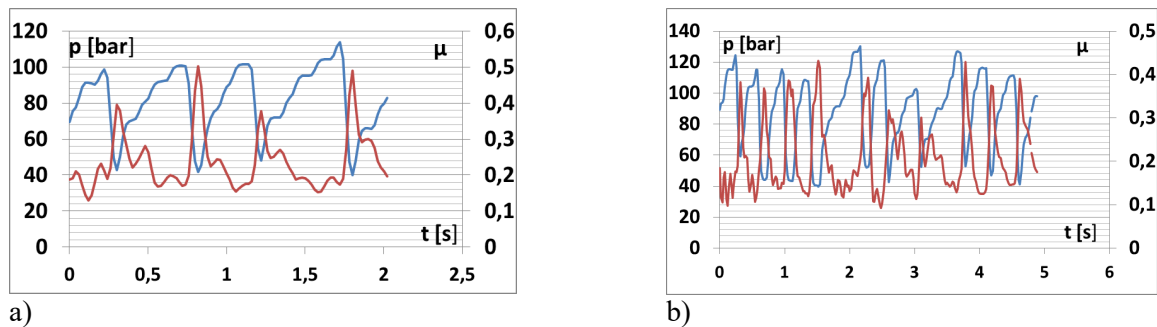
The conducted measurement allowed to obtain the characteristics of the change of pressure in brake caliper and the velocity and slip of vehicle's wheels. All the braking maneuvers were conducted at the initial velocity of 60 km/h. In figure 3, the course of the changes in brake caliper of pressure and friction coefficient during different braking maneuvers were presented. As it is visible on the diagrams, the courses of the changes of friction coefficient are characterized by high noise. On the following diagrams – figure 4, the course of the wheel slip during braking maneuver was shown. They depict the changes in the range of wheel slip used during braking. Pressure modulation in brake caliper transfers simultaneously to the changes of pressure on contact surface of brake pad and brake disk. The influence of pressure modulation in brake caliper on the course of changes of friction coefficient was shown in figure 5.



**Figure 3.** The course of pressure and friction coefficient during braking maneuver without ABS activation; a) constant pressure in brake caliper, dry surface of brake disc; b) variable pressure wet surface of brake disc; c) increasing pressure in brake caliper, dry surface of brake disc;

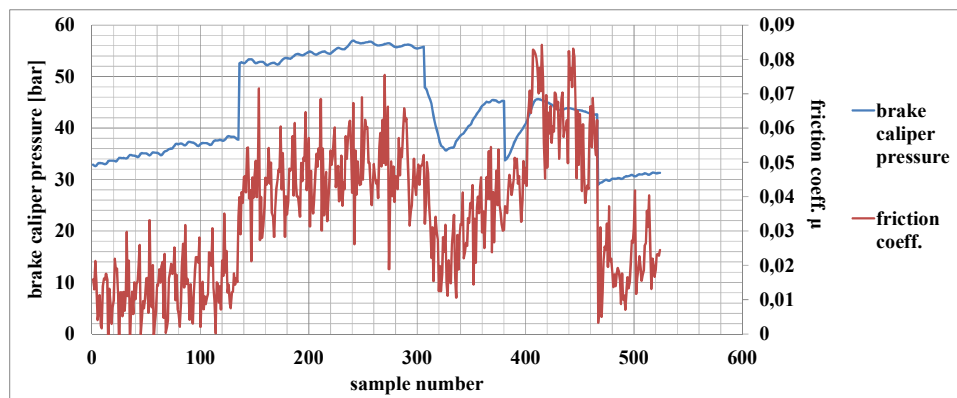


**Figure 4.** The course of wheel slip during braking maneuver; a) with ABS activation, dry surface of brake disc; b) with ABS activation, wet surface of brake disc; c) without ABS activation, wet surface of brake disc;



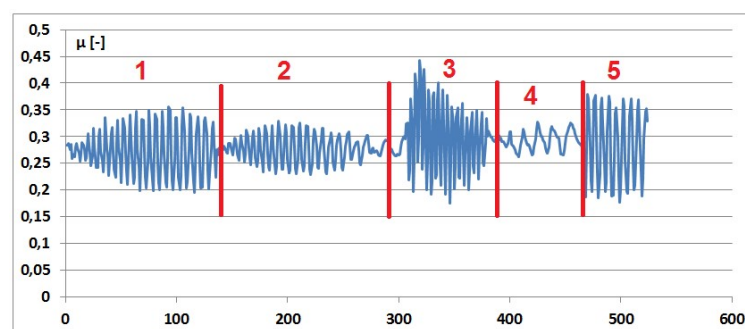
**Figure 5.** The course of pressure in brake caliper and friction coefficient during braking maneuver; a) with ABS activation, dry surface of brake disc; b) with ABS activation, wet surface of brake disc;

On the basis of the data obtained during the tests and the calculated values of friction coefficient, evaluation of the possibility of estimation of friction coefficient with the use of neural network was conducted. The assessment was carried out in case of braking maneuver with the activation of ABS and without it. Each calculation was done for two sets of data. The first case was braking with dry brake disc, the second one with wet brake disc. Matrix 2x524 constituted input data to the neural network model. The input parameters were as follows: pressure in brake caliper and wheel slip during braking maneuver what was shown in figure 6. Input data in figure are the parameters recorded during the tests. The character of slip variation corresponds to the character of pressure in brake caliper. It is depicted by the case of braking maneuver without ABS activation. Course of slip and pressure correspond to real conditions of the operation of brake system.



**Figure 6.** The course of input parameters: pressure in brake caliper and wheel slip during braking maneuver without ABS activation

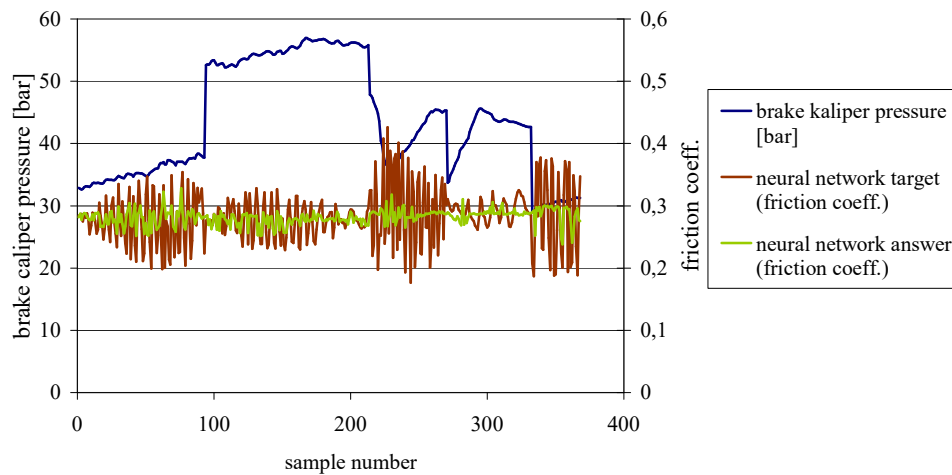
In figure 7 course of friction coefficient for different conditions of braking maneuver was presented. The presented course of friction coefficient constitutes an output matrix used for process of training a neural network and later the determination of corresponding error matrix. Friction coefficient recorded during test braking maneuvers constitutes data set of numeric outputs. In figure 7 the courses of friction coefficient recorded during particular rides were marked with the following numbers: 1- braking maneuver without ABS activation, increasing pressure in brake caliper, and dry surface of brake disc; 2- without ABS activation constant pressure in brake caliper, dry surface of brake disc; 3- variable, high pressure, wet surface of brake disc; 4- variable, low pressure, wet surface of brake disc; 5- medium pressure wet surface of brake disc.



**Figure 7.** The course of friction coefficient for braking without ABS activation and different conditions: 1- dry surface of brake disc, increasing pressure in brake caliper; 2- dry surface of brake disc, constant pressure in brake caliper; 3- variable, high pressure, wet surface of brake disc; 4- variable, low pressure, wet surface of brake disc; 5- medium pressure wet surface of brake disc

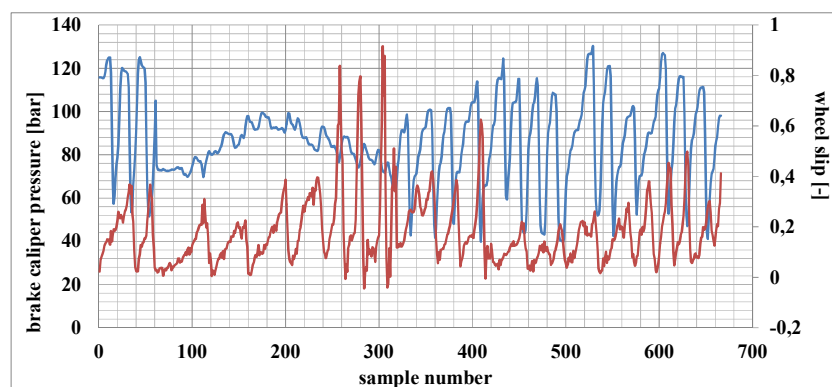
The course of error of output data presented in figure 8 confirms correctness of the method of estimation of friction coefficient. The errors of output data correspond to the course of changes of friction coefficient. The errors of output data were similar to all the matrices used for calculations. The use of neural network allows to estimate mean values of friction coefficient during braking maneuver for various friction conditions.





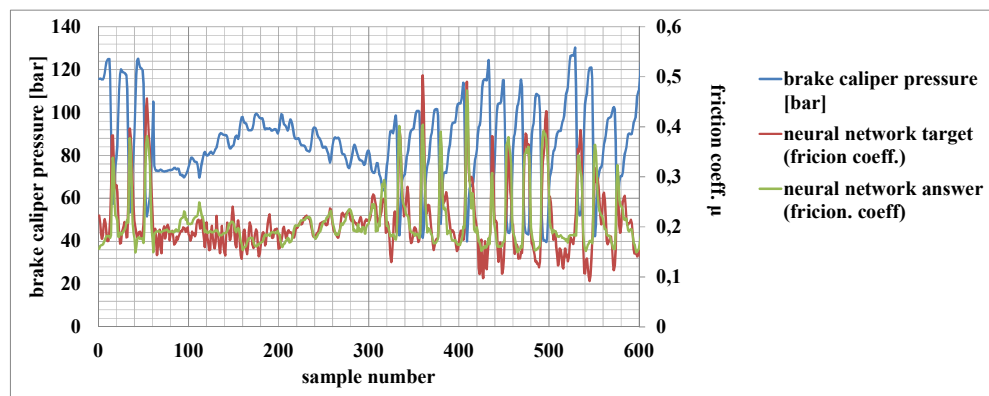
**Figure 8.** The comparison of the measured and estimated friction coefficient during braking maneuver without ABS activation

The next stage of the research was the analysis of the possibilities of using neural network which had already been used in case of panic braking with the activation of ABS system. Entry data including pressure in brake caliper and slip depicts rapid fluctuation of parameters resulting from the pressure modulation by ABS system. As it was previously, measurement was done with dry and wet brake disc. The entry data constitute matrix  $2 \times 666$ . The course of input parameters such as: pressure in brake caliper and wheel slip during braking maneuver was presented in figure 9.



**Figure 9.** The course of input parameters: pressure in brake caliper and wheel slip during braking maneuver

Due to the speed of the changes of input parameters, in comparison with their changes during braking without ABS activation, the error of estimating friction coefficient is larger. However, also in case of braking with ABS activation, the use of neural network allows to estimate mean values of friction coefficient during braking maneuver, what is illustrated in figure 10. The application of the suggested solution of neural network can allow for the increase of the precision of the control algorithms of active safety systems like for example ABS.



**Figure 10.** The comparison of the measured and estimated friction coefficient during braking maneuver with ABS activation

## 5. Conclusions

The brake pad properties have an essential meaning in automotive brake system and an influence on the effectiveness of braking. The demand for these elements concerns value and stability of the friction coefficient as well as the durability of the friction linings. From the point of view of efficiency of operation, the characteristics of the friction coefficient have a special meaning

The conducted tests of the course of the friction coefficient during vehicle braking process allowed to compare the efficiency of the system operation in different conditions. The used methodology is important since it can estimate friction coefficient during operation of disc brake systems.

On the basis of the conducted research we can draw the following conclusions, particularly:

1. The fluctuations of the friction coefficient can reach 40% during single braking. The changes of friction pair of brake disc and pad have an influence on this. The changes of operating conditions. are influenced by external factors. These are any contaminants which access the surface of the brake disc.
2. Particularly, the phenomenon offluctuations of the friction coefficient can be observed during ABS activation;
3. The neural network canestimate friction coefficient during single braking.
4. In spite of the fact that the reported observations are valid for the tested disc and pad combination, one can verify that the application of the suggested solution of neural network can allow for the increase of the precision of the control algorithms of active safety systems like ABS, for example.

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