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Creation of electric vehicle ABS operation algorithm with possibility of hybrid braking based on slip-slope approach at wheels slip determining

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Abstract. This paper represents an Anti-lock Braking System (ABS) operation algorithm implementing hybrid braking; the paper considers braking with a high deceleration of an electric passenger vehicle during the rectilinear driving on the roads with different friction coefficients; a short analysis of the approaches used for evaluation of the target vehicle wheels slip is also performed. The main ABS task consists in maintenance of the target wheel slip coefficient based on the tyre-road friction coefficient. The tyre-road friction coefficient φ_x is determined using the algorithm proposed in the papers by Semmler. The algorithm is about finding the curve peak $\varphi_x - S$ using the least square method. Based on the calculated target slip coefficient, the braking torque at the electric motor shaft operating in the regeneration mode is determined. The electric motor ensures relatively low braking torque at the vehicle wheels preventing the tyres from a significant slip. Reaching the target slip coefficient is ensured by means of friction brake mechanisms. Virtual tests showed that the values of the wheel slip coefficient are close to the required ones. Thus, this system makes it possible to implement hybrid braking with two sources creating the brake torque.

Introduction

The Anti-lock Braking System (ABS) serves to prevent vehicle wheels lock-up in order to maintain steerability as well as to reduce the vehicle braking distance. An increase in the number of papers dedicated to ABS integration with other vehicle systems can recently be observed in foreign sources [1, 2]. One of the special cases of such integration is the use of a traction electric motor, which operates in the energy regeneration mode, within ABS in electric vehicles. It should be noted that, at the moment, there is no unified control strategy accepted for the process of combined braking by means of the friction brake mechanisms and electric motor, which operates in the energy regeneration mode. One of the possible variants of combining two brake torque sources is considered in this paper.

ABS Structure

The vehicle Anti-lock Braking System is a control system with feedback (Figure 1).

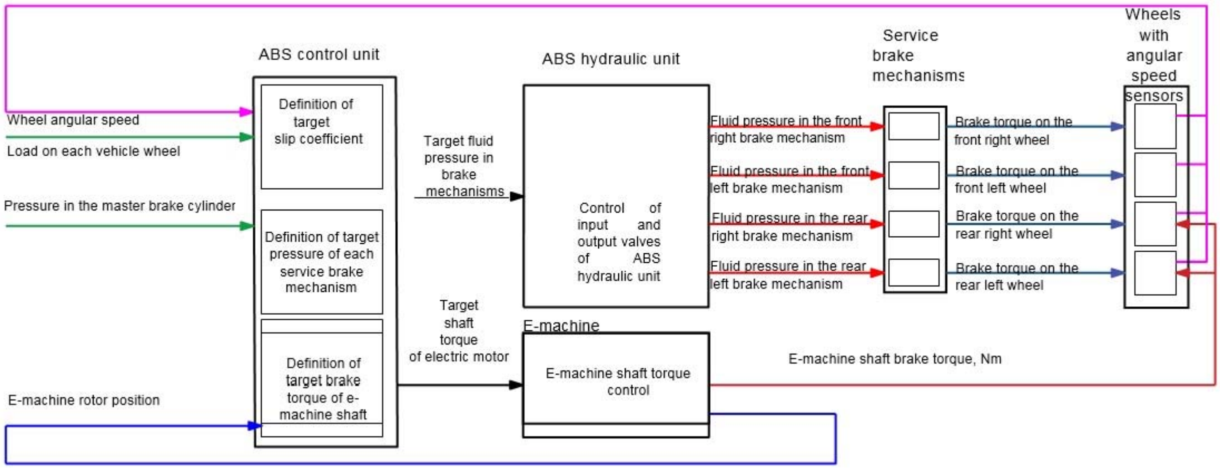

Figure 1. ABS diagram.

The system consists of the following components:

1. Control unit responsible for calculation of the target slip coefficient, as well as for control of the hydraulic unit valves and electric motor of the vehicle.
2. Hydraulic unit, which is an actuator ensuring adjustment of pressure in the service brake mechanisms.
3. Wheels angular speed sensors, which are tracking devices used in order to ensure the feedback.
4. Vertical load sensors, which are tracking devices ensuring acquisition of information about the vertical load on each wheel.

Target wheels slip coefficient determination method

The maximum axial force Fx exerted upon the vehicle is known to be proportional to the tyre-road friction coefficient μ (1).

$$F_x = F_z \cdot \mu, \tag{1}$$

In turn, the tyre-road friction coefficient μ depends on the tyre-road slip coefficient S. The example of this dependence is given in Figure 2.

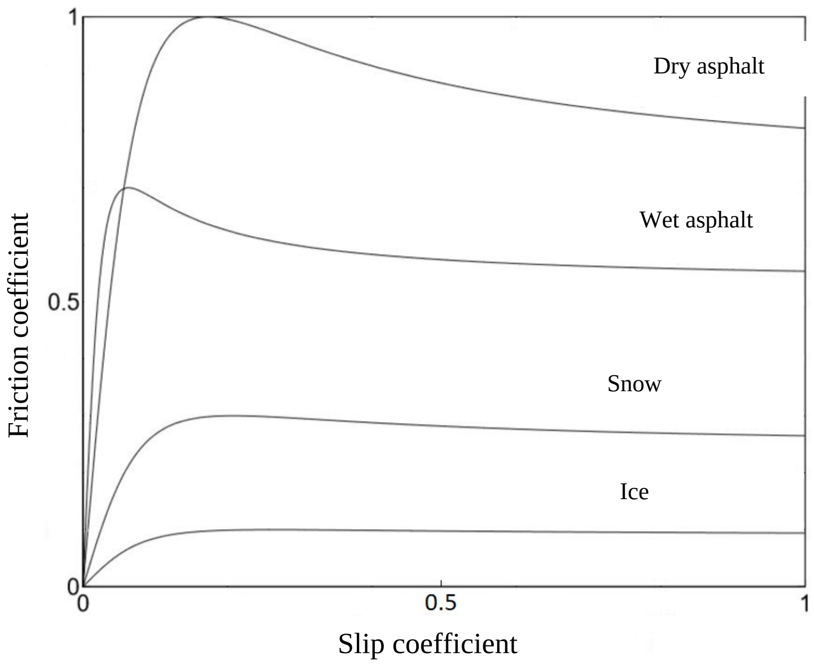

Figure 2. Dependence of friction coefficient on slip coefficient.

For assessment of the tyre-road friction that is the maximum for the given conditions, many papers suggest using the models that describe the interaction of tyres with the bearing surface – mathematical, analytical or empirical ones. The most common tyre models are the models based on the Magic Formula [3], Brush model [4, 5] and others [6]. This approach ensures a high-precision definition of the maximum tyre-road friction coefficient, but it has a number of considerable disadvantages:

1. The models become complicated when it is necessary to consider the slip due to the tyre properties – pressure, tyre tread wear, foreign bodies in the contact area, tyre and bearing surface temperatures.

2. High difficulty of obtaining an accurate tyre model caused by the need to conduct a large number of experiments.

3. Complexity of adjustment of the surface properties estimator during real experiments.

4. Methods of model parametrization based on experimental data demand acquisition and systematization of a large scope of information.

An alternative approach for the definition of the bearing surface friction properties is the slip-slope approach.

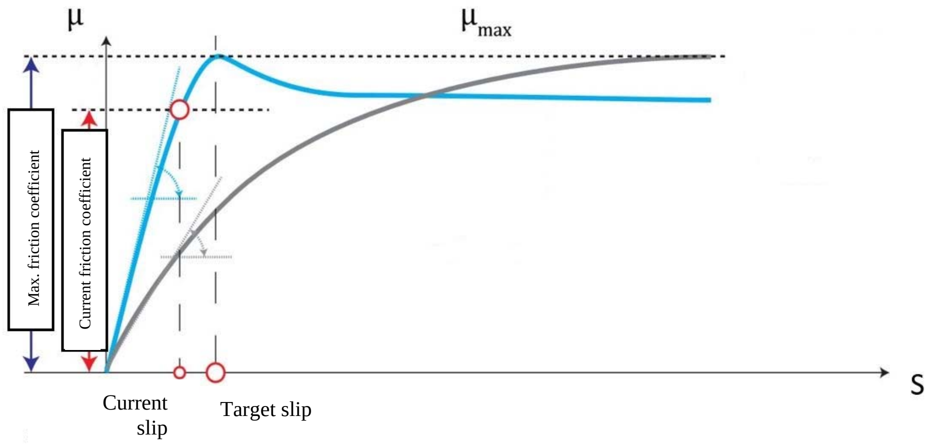

Figure 3. Difference in tangent slope angles at different tyre-road friction coefficients.

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As one can see in Figure 3, the tangent slope angle against the curve describing the μ-S function for different friction coefficients of the bearing surface may vary within a quite wide range. This observation became a basis for the slip-slope approach applied for the determination of the maximum tyre-road friction coefficient.

Compared to the methods based on the tyre models only, the methods using the slip-slope approach are characterized by a much smaller number of variables necessary for the correct operation of ABS controllers with the given accuracy as well as by convenience of adjusting the models under the real experiment conditions.

One of the methods for the target slip coefficient determination using the slip-slope approach is the method suggested in Semmler's papers [7]. The process of determination of the target slip coefficient according to this method can be divided into three stages:

1. Determination of a μ-S diagram section containing W points with T time step.
2. Determination of the optimum slip.
3. Setting the value of the target slip.

Determination of the μ-S diagram section is performed by means of approximation of W points characterizing the S slip coefficient and μ tyre-road friction coefficient with the T time step, by a straight line (2).

$$\mu(k) = c_0 + c_1 \cdot S(k), \tag{2}$$

Applying the least square method, it is possible to obtain the value of coefficient c_1 characterizing this line slope. Thus, it is possible to draw a conclusion, whether the average slip coefficient of the considered wheel is higher or lower than the optimum value. In case of c_1 sign reversal, it is supposed that the average slip coefficient of the considered wheel has passed the μ-S curve peak. Thus, the optimum slip coefficient S_{opt} is calculated according to the following formula (3):

$$S_{opt} = \frac{1}{W} \cdot \sum_{i=0}^{W} S(i) \; \forall \; sgn(c_1(k)) \neq sgn(c_1(k-1)), \tag{3}$$

As the target slip shall not considerably deviate from the maximum value, but, at the same time, change of the target slip within the small range about the optimum slip is necessary for obtaining the μ-S curve maximum, the author suggests using the following formula in order to define the target slip S_d (4):

$$S_d(k) = \begin{cases} S_d(k-1) + K_S \cdot sgn\left(S_{opt}(k) - S_d(k-1)\right) & \forall sgn\left(c_1(k)\right) = sgn(c_1(k-1)) \\ S_{opt}(k) & \forall sgn(c_1(k)) \neq sgn(c_1(k-1)) \end{cases}, \tag{4}$$

Following the tests, this approach showed the exact definition of μ-S curve peak on surfaces with any tyre-road friction coefficient ranging from 0.1 to 1. As a result, this method is well applicable in ABS algorithms.

Vehicle wheel brake torque control algorithm

A rear-wheel-drive electric vehicle of N2 category, the necessary specifications of which are given in Table 1, was selected as an object of investigation for this paper.

Table 1. Specifications of N2 category vehicle.

Fully loaded weight	4200 kg
Weight on front axle	1653 kg
Weight on rear axle	2547 kg
Unladen weight	4060 kg
Weight on front axle	1555 kg
Weight on rear axle	2505 kg
Height of the center of mass	
Unladen condition	998 mm
Fully loaded weight	1001 mm
Tyres	185/75R16C

The characteristics of an e-machine applied in the examined vehicle are shown in Figure 4 [8].

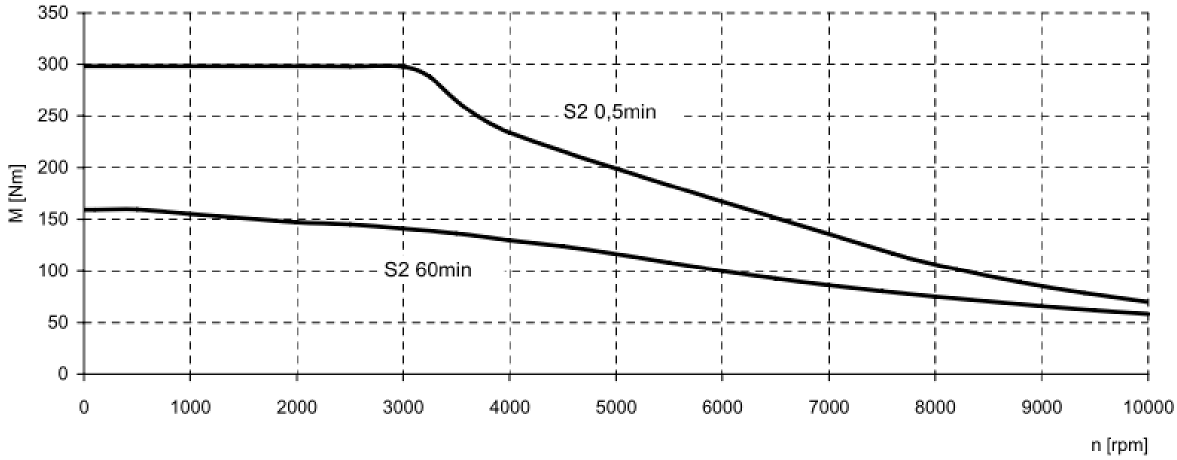

Figure 4. E-machine characteristics.

The brake torque control on the driving wheels is exercised by means of controlling the brake torque from the e-machine operating in the regeneration mode, as well as by controlling the brake mechanisms pressure. The brake torque control on the driven wheels is exercised only by means of brake fluid pressure control in brake mechanisms.

It should be noted that, in this vehicle configuration, the maximum brake torque created by the e-machine does not allow reaching thigh brake efficiency when driving on a surface with friction coefficient higher than 0.3. When driving on a road with the tyre-road friction coefficient less than 0.3, the brake torque from the e-machine is limited and does not reach the maximum value. It is reasonable to exclude PID control of the e-machine shaft torque for the wheel slip control described in [9] in view of the complexity of system adjustment when changing the brake torque source.

The vehicle wheel slip coefficient is adjusted by changing the brake fluid pressure in the service brake mechanisms in the ABS hydraulic unit. The hydraulic unit of the system is a device that controls the pressure in the service brake mechanisms of the vehicle. Each service brake mechanism is connected with the brake master cylinder by means of two valves – input valve and output valve. In the course of service braking characterized by low wheel slip coefficient, the input valve is opened and the output valve is closed. As soon as the wheel slip coefficient surpasses the preset limits, upon a signal from the ABS control unit, the input valve will be closed thus maintaining a constant pressure in the service brake mechanism. If the wheel slip coefficient continues to increase, the output valve will be opened and, as a result, the pressure in the service brake mechanism will decrease. As soon as the wheel slip coefficient reaches the preset value, the output valve will be closed.

The target brake pressure is calculated for each wheel by means of the PID controller. The feedback is performed by monitoring the wheels slip coefficient values. The control error is calculated as a difference between the target slip coefficient (obtained with application of Semmler's method) and actual slip coefficient.

System operation results

For system testing, a number of virtual tests were carried out according to the following scheme:

1. Initial driving speed – 101 km/h, accelerator pedal travel – 0%.
2. After reaching 100 km/h: accelerator pedal travel – 0%, brake pedal travel – 100%.
3. Braking up to 20 km/h.

These tests were carried out on roads with tyre-road friction coefficient μ=0.8 and 0.1.

Figure 5 shows the process of definition of the target front right wheel slip coefficient by the module when driving on the road with μ=0.8.

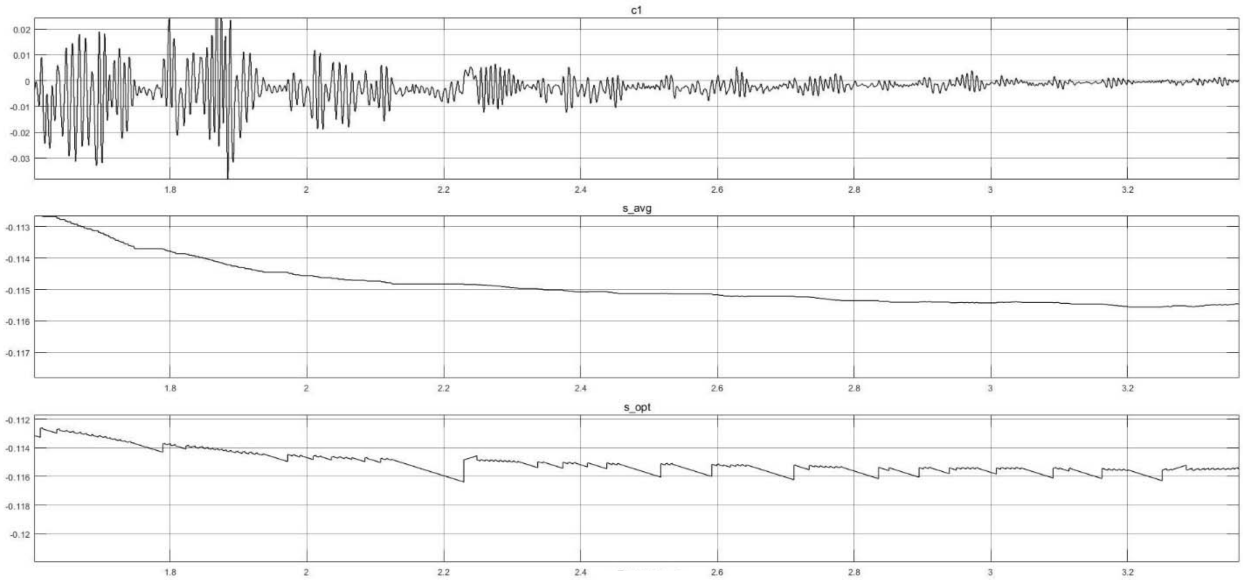

Figure 5. Process of definition of target front right wheel slip coefficient by module at μ=0.8.

Diagrams of wheel slip coefficient vs time on the road with μ=0.8 and 0.1 are shown in Figures 6 and 7, respectively.

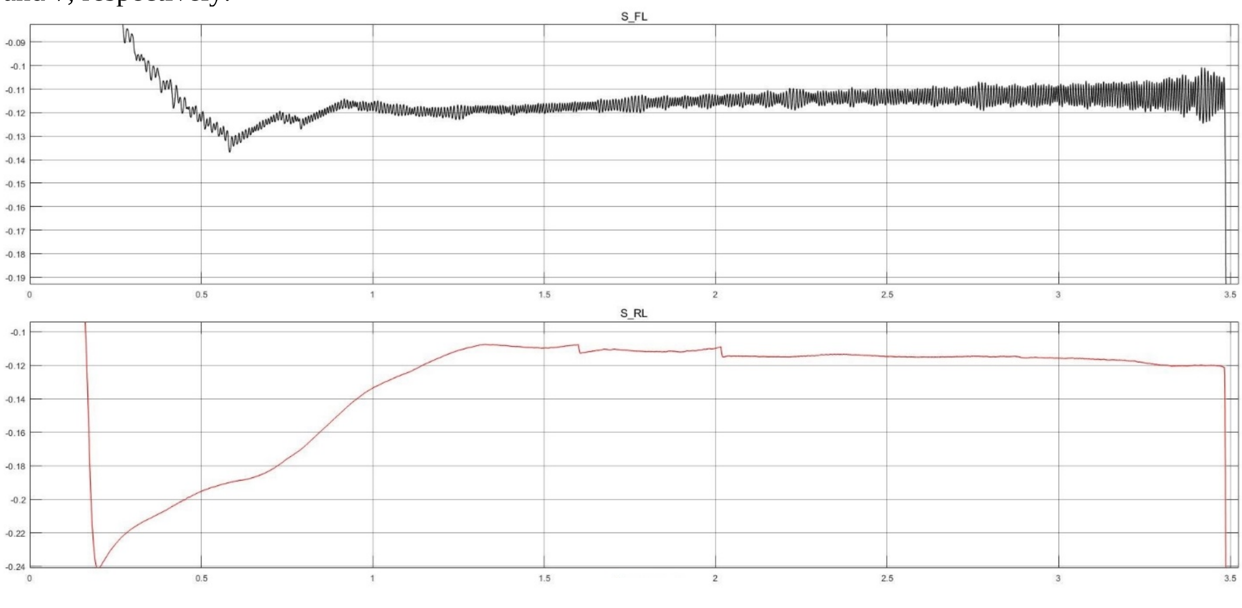

Figure 6. Change of wheel slip coefficient vs time on the road with μ=0.8.

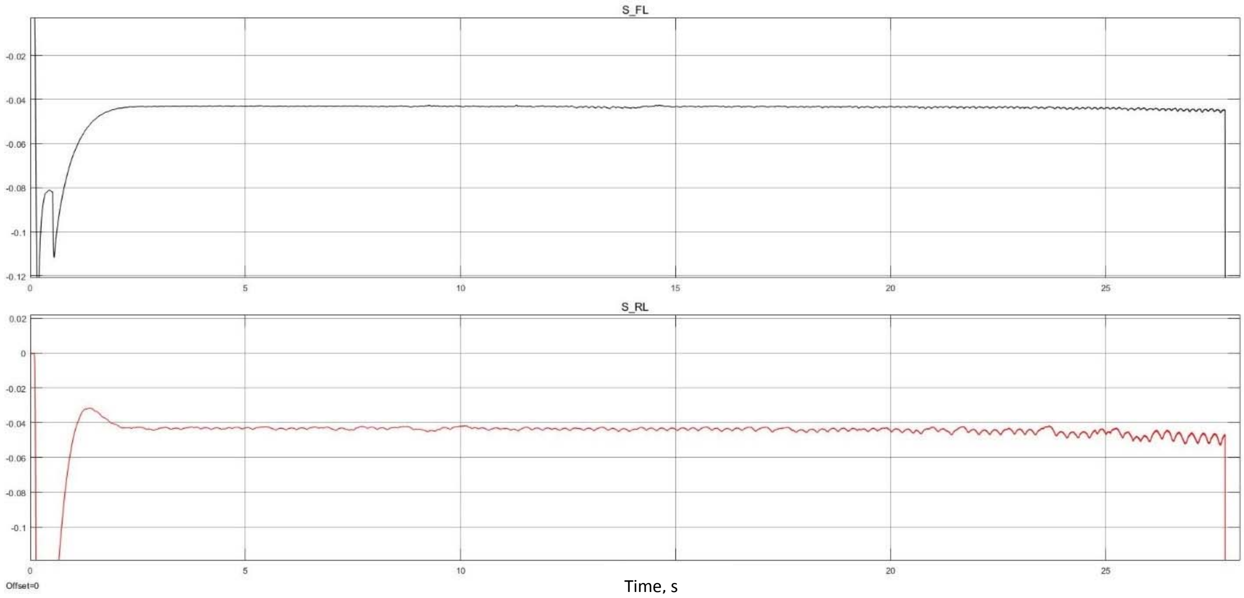

Figure 7. Change of wheel slip coefficient vs time on the road with μ=0.1.

It should be noted that the Anti-lock Braking System presented in this paper allows reduction of the vehicle braking distance by 5-10% in comparison to the "classic" system that does not use PID control. The braking distances for the developed system and for the "classic" system are provided in Table 2.

Table 2. Comparison of braking distance for different ABS algorithms.

Friction coefficient μ	Braking distance, m	
	With the developed system	"Classic" system
0.8	56.6	62.3
0.1	167.5	175.8

Conclusion

Summarizing the abovementioned, it is possible to draw several conclusions:

1. Application of the Slip-slope approach (in particular the Semmler's method) allows reaching the friction coefficient that is close to the maximum on the majority of pavings at any moment, which, in turn, reduces the vehicle braking distance by the value up to 10% in comparison to the "classic" braking algorithm.
2. The easiest adjustment refers to the hybrid braking system, in which the wheel slip is controlled only by one brake torque source.
3. The maximum efficiency of the developed system is reached when braking on roads with a high tyre-road friction coefficient. The braking distance on roads with μ=0.8 decreases by 5.7 meters compared to the "classic system". On roads with μ=0.1, the braking distance decreases by 8.3 meters.

References

[1] Savitski D, Ivanov V, Augsburg K, Pütz T and Barber P 2016 The new paradigm of an anti-lock braking system for a full electric vehicle: Experimental investigation and benchmarking *Proceedings of the Institution of Mechanical Engineers* Part D: Journal of Automobile Engineering
[2] Ivanov V, Augsburg K, Savitski D, Schreiber V, Els S and Dhaens M 2017 Collaborative engineering of integrated chassis control for ground vehicle: Case study of lifelong learning technologies in automotive mechatronics *2017 IEEE International Conference on Mechatronics (ICM)* Churchill VIC pp 449-454

[3] Pacejka H 2012 *Tire and Vehicle Dynamics* (Butterworth-Heinemann: Oxford, UK)
[4] Zhao J, Zhang J and Zhu B 2014 Developmentand Verification of the Tire/Road Friction Estimation Algorithm for Antilock Braking System *Math. Probl. Eng*. (doi:10.1155/2014/786492)
[5] Singh K and Taheri S 2014 Estimation of tire-road friction coefficient and its application in chassis control systems *Syst. Sci. Control Eng*. **3** pp 39–61
[6] Rajamani R 2012 *Vehicle Dynamics and Control* (Springer: New York, NY, USA)
[7] Semmler S 2006 Control of the vehicle brake dynamics with continuously adjustable wheel brakes *VDI Series 12* **632** (Dusseldorf)
[8] Information on http://media3.ev-tv.me/Azure300VDC-400Acurve.pdf
[9] Bakhmutov S V, Ivanov V G, Karpukhin K E and Umnitsyn A A 2018 Creation of operation algorithms for combined operation of anti-lock braking system (ABS) and electric machine included in the combined power plant *IOP Conference Series: Materials Science and Engineering* **315**(1)