Comparative assessment of vehicle anti-lock braking system operation using friction brake mechanisms and e-machine in the vehicle with electric drive of traction wheels

S V Bakhmutov\textsuperscript{1}, A A Umnitsyn\textsuperscript{1} and V G Ivanov\textsuperscript{2}

\textsuperscript{1} FSUE "NAMI", 2 Avtomotornaya St., Moscow, 125438, Russia
\textsuperscript{2} Research Professor TU Ilmenau, Ilmenau, Germany

E-mail: artem.umnicin@nami.ru

Abstract. Study of the braking process of the vehicle with an electric machine in the traction wheels drive equipped with an anti-lock braking system (ABS), where the actuators are the electric machine and friction brake mechanisms, is a relevant task. This is related to the worldwide trending increase in the share of production of vehicles with an electric machine within the transmission. In this paper, the "traditional" ABS and two systems with different variants of usage of the electric machine and friction brake mechanisms as actuators are compared: 1. The electric machine fulfills the function of the wheel slip regulator; the friction brake mechanisms maintain constant pressure in the brake line, which depends on the tyre-road friction coefficient. 2. The friction brake mechanisms fulfill the function of the wheel slip regulator; the electric machine maintains the set brake torque. According to the study results, usage of the combined actuator system within the ABS allows reducing the braking distance significantly, raising the vehicle deceleration value and improving the driver's and passengers' comfort during braking.

1. Introduction
The Anti-lock Braking System (ABS) is an important vehicle system having direct effect on traffic safety. One of the latest trends in the development of this system is the use of an e-machine as one of the actuators. In recent years, this has been connected, first of all, with the considerable increase in sales of electric vehicles and vehicles equipped with a hybrid power unit \cite{ref1, ref2}. Studying the properties and methods for control of the modern anti-lock braking system is an important and relevant task of the automotive industry \cite{ref3, ref4}. A comparative analysis of the previously developed anti-lock braking system operation algorithm \cite{ref5} with continuous control and the traditional system with rule-based control is performed within this paper.

2. Object of investigation
In this paper, the object of investigation is the mathematical model of the rear-wheel-drive electric vehicle of category N2, the key specifications of which are given in Table 1.
### Table 1. Specifications of N2 category vehicle.

| Specification                          | Value     |
|----------------------------------------|-----------|
| Fully loaded weight                    | 4200 kg   |
| Weight on front axle                   | 1653 kg   |
| Weight on rear axle                    | 2547 kg   |
| Unladen (kerb) weight                  | 4060 kg   |
| Weight on front axle                   | 1555 kg   |
| Weight on rear axle                    | 2505 kg   |
| Height of the center of mass:          |           |
| in the unladen weight condition        | 998 mm    |
| with fully loaded weight               | 1001 mm   |
| Tyres                                  | 185/75R16C|

The characteristics of the electric machine used in this model are shown in figure 1, [6].

![Characteristics of electric machine.](image)

**Figure 1.** Characteristics of electric machine.

### 3. Variants of ABS actuator control

At the moment, there are two main types of ABS actuator control:

1. Continuous control that is characterized by constant control of pressure in the wheel brake cylinders, which ensures reduction of wheel slip oscillation amplitude relative to the target value, and also enables application of the electric machine as an actuator.

2. Rule-based control that implies setting the slip boundaries according to which the pressure in the wheel brake cylinders is controlled. Such approach is the most reliable and easy to set up, but at the same time, it does not allow achieving low wheel slip oscillation relative to the target value, as a result, the braking distance may be increased and the driver and passenger comfort worsened, it also makes it difficult to use the advantages of the electric machine as an ABS actuator to the full extent.

3 variants of ABS actuator control are considered within this work.

1. Control type: constant. Actuators: friction brake mechanisms and electric machine. Slip is regulated by the electric machine. The algorithm monitors the electric machine load and, if necessary, smoothly adjusts the pressure in the rear wheel brake lines. The target pressure in the front brake mechanisms and the target electric machine torque are determined by PID controllers.

2. Control type: constant. Actuators: friction brake mechanisms and electric machine. Slip is regulated by the friction brake mechanisms. The algorithm monitors the pressure in the rear brake mechanism brake lines and, in case of exceeding a certain threshold, raises the electric machine brake torque smoothly. In case the pressure falls to the set threshold, the electric machine brake torque decreases. The target pressure in the brake mechanisms is determined by the PID controllers.
3. Control type: rule-based. Actuators: friction brake mechanisms. The minimum and maximum slip thresholds are defined as the optimum one ± 0.01. If the current wheel slip value is above the threshold one (max.), the pressure is decreased. If the current slip is below the threshold one (min.), the pressure is increased. If the current slip is between the minimum and maximum threshold values, the pressure is maintained. The e-machine is not involved in braking.

Definition of the wheel slip target values in all cases is performed by the method specified in paper [5]. The anti-lock braking system layout and general information are presented in paper [7].

4. Virtual test method

The following virtual test conditions are suggested for the evaluation of the operation efficiency of the control variants described above.

1. Initial speed: 60 and 100 km/h.
2. Wheel adhesion coefficient during driving: 0.8 and 0.2.
3. The accelerator pedal is completely released.
4. The brake pedal is pressed with 300 N force.
5. Upon decelerating to 15 km/h, the test stops.

5. Criteria for ABS operation efficiency evaluation

The criteria for the ABS operation efficiency evaluation used in this paper are taken from paper [7]. The ABS operation efficiency is assessed according to 6 criteria:

1. Braking distance.
2. Average deceleration.
3. ABS index of performance (ABSIP) equal to the ratio between the average deceleration during the ABS operation and the average deceleration when braking without the ABS.
4. Average slip.
5. Slip control peak-to-peak value, which is characterized by the percentage ratio of the difference between the maximum and minimum wheel angular speed to the maximum wheel angular speed at the start of ABS operation.
6. ITAE Jerk – integral of the absolute value of the derivative of acceleration times the time.

6. Comparative assessment of anti-lock braking system algorithms operation

Table 2 contains the parameters of the assessment criteria for the ABS operation efficiency during braking at 60 km/h.

| Control variant | Braking parameters | ABS operation parameters |
|-----------------|-------------------|-------------------------|
|                 | Braking distance, m | Average deceleration, m/s² | ABSIP | Average slip, % | Peak-to-peak value, front axle, % | Peak-to-peak value, rear axle, % | Jerk ITAE |
|-----------------|-------------------|-------------------------|-------|----------------|-------------------------------|---------------------|----------|
| Variant 1       | 75.86             | -1.75                   | 1.11  | -5.93          | 60.86                        | 4.401               | 1.59     |
| Variant 2       | 76.13             | -1.74                   | 1.11  | -7.61          | 61.35                        | 61.48               | 3.51     |
| Variant 3       | 81.59             | -1.61                   | 1.02  | -24.5          | 14.39                        | 7.8                 | 76.40    |
| without ABS     | 83.13             | -1.58                   | 1.00  | -98.74         | -                            | -                   | -        |
| µ=0.2           |                   |                         |       |                |                              |                     |          |
| Variant 1       | 21.20             | -6.47                   | 1.07  | -15.59         | 6.63                         | 31.84               | 3.42     |
| Variant 2       | 20.81             | -6.55                   | 1.08  | -20.87         | 10.65                        | 17.7                | 3.80     |
| Variant 3       | 20.75             | -6.48                   | 1.07  | -24.66         | 4.1                          | 2.95                | 52.50    |
| without ABS     | 22.21             | -6.04                   | 1.00  | -92.88         | -                            | -                   | 17.55    |
| µ=0.8           |                   |                         |       |                |                              |                     |          |
Figure 2 provides circular radar charts with indicators according to the assessment criteria for the ABS operation efficiency during braking at 60 km/h.

\[ \mu = 0.2 \]

\[ \mu = 0.8 \]

Table 3 provides indicators of the assessment criteria for the ABS operation efficiency during braking at 100 km/h.

**Table 3.** Summary table of assessment criteria for ABS operation efficiency during braking at 100 km/h

| Control variant | Braking parameters | ABS operation parameters |
|-----------------|--------------------|--------------------------|
|                 | Braking distance, m | Average deceleration, m/s² | ABSIP | Average slip, % | Peak-to-peak value, front axle, % | Peak-to-peak value, rear axle, % | Jerk ITAE |
| Variant 1       | 219.80             | -1.73                    | 1.08   | -5.93           | 60.86                        | 4.401                          | 1.59     |
| Variant 2       | 213.90             | -1.78                    | 1.11   | -7.61           | 61.35                        | 61.48                          | 3.51     |
| Variant 3       | 227.70             | -1.65                    | 1.03   | -24.5           | 14.39                        | 7.8                            | 76.40    |
| without ABS     | 234.90             | -1.60                    | 1.00   | -98.74          | -                            | -                              | -        |
| Variant 1       | 58.85              | -6.64                    | 1.07   | -15.59          | 6.63                         | 31.84                          | 3.42     |
| Variant 2       | 56.88              | -6.85                    | 1.11   | -20.87          | 10.65                        | 17.7                           | 3.80     |
| Variant 3       | 57.60              | -6.67                    | 1.08   | -24.66          | 4.1                          | 2.95                           | 52.50    |
| without ABS     | 62.11              | -6.19                    | 1.00   | -92.88          | -                            | -                              | 17.55    |
Figure 3 provides the circular radar chart with indicators according to the assessment criteria for the ABS operation efficiency during braking at 100 km/h.

**Figure 3.** Circular radar chart with indicators according to the assessment criteria for ABS operation efficiency during braking at 100 km/h.

It may be noted that variant 3, currently applied in most vehicles, provides the worst efficiency among the considered variants.

Variant 1 – continuous control where the slip is controlled by the e-machine – compared to Variant 3, in case of braking from 60 km/h on the road with adhesion coefficient $\mu=0.2$, reduces the braking distance by 7%, and in case of braking on the road with adhesion coefficient $\mu=0.8$, the braking distance is increased by 2.2%. In case of braking from 100 km/h speed on the road with adhesion coefficient $\mu=0.2$, this variant reduces the braking distance by 3.5%, and in case of braking on the road with adhesion coefficient $\mu=0.8$, the braking distance is increased by 2.2%.

Variant 2 – continuous control where the slip is controlled by the friction braking mechanisms, and the electric motor only generates constant torque – ensures the best parameters of the anti-lock braking system efficiency. In case of braking from 60 km/h speed on the road with adhesion coefficient $\mu=0.2$, this variant, compared to the third one, reduces the braking distance by 6.7%, but in case of braking on the road with adhesion coefficient $\mu=0.8$, the braking distance is increased by 2.2%. In case of braking from 100 km/h speed on the road with adhesion coefficient $\mu=0.2$, this variant reduces the braking distance by 6.1%, and in case of braking on the road with adhesion coefficient $\mu=0.8$, the braking distance is reduced by 1.3%.

7. Conclusion

Comparing two types of the anti-lock braking system, it can be noted that the constant control has a number of advantages in comparison with the threshold one, especially when used in the vehicles equipped with an electric machine within the vehicle transmission. On the other hand, the presence of the differential located between the electric machine and the vehicle wheels does not allow exploiting all the advantages of the individual wheel slip control by means of electric machines [8]. Thus, it is more efficient to use variant 2 of the algorithm presented in this paper in case of usage of one electric machine within the ABS.
References

[1] Terenchenko A S, Karpukhin K E, Kurmaev R 2015 Features of Operation of Electromobile Transport in the Conditions of Russia 28th International Electric Vehicle Symposium and Exhibition 2015 28

[2] Karpukhin K E, Terenchenko A S 2016 Features of Creation and Operation of Electric and Hybrid Vehicles in Countries with Difficult Climatic Conditions in the Russian Federation IOP Conference Series: Materials Science and Engineering 2016 157 № 1 p 012014

[3] Kamenev V F, Terenchenko A S, Karpukhin K E, Kolbasov A F 2017 The strategy of creating urban electric vehicle: Challenges and solutions International Journal of Civil Engineering and Technology 8 Issue 12

[4] Karpukhin K E, Terenchenko A S 2017 The specificity of the popularization of hybrid and electric vehicle in the Russian Federation EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition

[5] Bakhmutov S V, Umnitsyn A A, Ivanov V 2019 Creation of electric vehicle abs operation algorithm with possibility of hybrid braking based on slip-slope approach at wheels slip determining, IOP Conference Series: Materials Science and Engineering

[6] http://media3.ev-tv.me/Azure300VDC-400Acurve.pdf

[7] Bakhmutov S V, Ivanov V, 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

[8] Savitski D, Ivanov V, Augsburg K, Pütz T, 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