Intelligent anti-lock braking system of electric vehicle with the possibility of mixed braking using fuzzy logic

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Abstract. This article discusses the work of an intelligent anti-lock braking system (ABS), in which electric machines and friction brakes act as actuators. Combining several actuators at one control object is a difficult task. One of the possible ways to solve it is the use of a control system based on fuzzy logic. The paper compares two tracking algorithms for controlling the actuators of the anti-lock braking system: - slipping control using mixed braking, with a control system based on fuzzy logic; - slipping control by means of braking by one actuator - friction brakes. Research results have shown that the use of mixed braking allows one to increase the performance of this system in various driving conditions.

1. Introduction
An electric car, as an actuator of an intelligent anti-lock braking system, has a number of advantages in comparison with a friction brake mechanism:

1) Higher accuracy of creating and maintaining the target braking torque on the wheel shaft;
2) Higher performance;
3) Possibility of recuperating the kinetic energy of the vehicle movement.

On the other hand, an electric machine cannot be used as the only source of braking torque, which is dictated by a number of factors, namely: low braking torque (in comparison with a frictional braking mechanism); the dependence of the braking torque on the state of the high-voltage battery; complexity of the system as a whole.

Thus, the use of electric machines and friction brakes in an anti-lock braking system as actuators is associated with difficulties connected with the control of several actuators at one control object.

2. Object of investigation
The object of investigation within this paper is the all-wheel drive M1 category electric vehicle with individual wheel drive, some of the technical parameters and characteristics of which are given in Table 1.
Table 1. M1 category electric vehicle technical characteristics.

| Parameter                                          | Value        |
|----------------------------------------------------|--------------|
| Sprung weight                                      | 1,712 kg     |
| Wheelbase                                          | 2,662 mm     |
| Distance from the center of mass to the front wheel| 1,072 mm     |
| Height of the center of mass                       | 714 mm       |
| Transmission ratio                                 | 10.5         |
| Dependence of the brake torque on the pressure in the brake system for the front wheels | 406.7 N·m/MPa |
| Dependence of the brake torque on the pressure in the brake system for the rear wheels | 173.2 N·m/MPa |
| Tyres                                              | 235/55R19    |

3. Control object model

To describe vehicle motion, a mathematical model with 14 degrees of freedom was used. The vehicle model includes the following submodels: the body model, suspension model, wheel model.

To describe vehicle motion, a fixed system of reference linked to the bearing surface is taken. It has the following direction of axes: X axis – in the direction of vehicle longitudinal motion, Y axis – to the right, relative to the vehicle longitudinal axis, Z axis – vertically downwards.

The body model is characterized by six degrees of freedom. Direction of $X_1$, $Y_1$, $Z_1$ axes of the moving system of reference of the body initially coincides with the direction of axes of the fixed system of reference, and the reference point (origin of coordinates) coincides with the center of gravity. The body model is described by the following expressions:

\[
\vec{F}_b = m \left( \vec{V}_b + \vec{\omega} \times \vec{V}_b \right) \quad (1)
\]

\[
\vec{M}_b = I \vec{\omega} + \vec{\omega} \times (I \vec{\omega})
\]

\[
I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}
\]

where: $F_b$ – force acting on the vehicle body; $m$ – body weight, $V_b$ – vehicle body motion speed (relative to the fixed system of reference); $\omega$ – vehicle body angular speed (relative to the fixed system of reference); $I$ – moment of inertia of the body.

The relation between the body angular speed vector and the rate of change of Euler angles shall be defined as follows:

\[
\omega = \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\tau} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \varphi & \sin \varphi \\ 0 & -\sin \varphi & \cos \varphi \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ \dot{\tau} \end{bmatrix}
\]

\[
+ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\varphi} \\ \dot{\psi} \end{bmatrix} = J^{-1} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}
\]

where $p$, $q$, $r$ – body angular speed vector projection on axes $X_1$, $Y_1$, $Z_1$; $\varphi$, $\theta$, $\tau$ – Euler angles.

Force $F_b$ and torque $M_b$ acting on the vehicle body can be described in the following expressions:
\[ \vec{F}_b = \begin{bmatrix} F_{g \cos \theta} \\ F_{g \cos \beta} \\ F_{g \cos \theta} \end{bmatrix} + \begin{bmatrix} F_{FLx} \\ F_{FLy} \\ F_{FLz} \end{bmatrix} + \begin{bmatrix} F_{FRx} \\ F_{FRy} \\ F_{FRz} \end{bmatrix} + \begin{bmatrix} F_{RLx} \\ F_{RLy} \\ F_{RLz} \end{bmatrix} + \begin{bmatrix} F_{RRx} \\ F_{RRy} \\ F_{RRz} \end{bmatrix} + \begin{bmatrix} F_{ax} \\ F_{ay} \\ F_{az} \end{bmatrix} \] (5)

\[ \vec{M}_b = \begin{bmatrix} M_{ax} \\ M_{ay} \\ M_{az} \end{bmatrix} + \begin{bmatrix} M_{FLx} \\ M_{FLy} \\ M_{FLz} \end{bmatrix} + \begin{bmatrix} M_{FRx} \\ M_{FRy} \\ M_{FRz} \end{bmatrix} + \begin{bmatrix} M_{RLx} \\ M_{RLy} \\ M_{RLz} \end{bmatrix} + \begin{bmatrix} M_{RRx} \\ M_{RRy} \\ M_{RRz} \end{bmatrix} \] (6)

where: \( F_g \) – force of gravity; \( F_{FL}, F_{FR}, F_{RL}, F_{RR}, M_{FL}, M_{FR}, M_{RL}, M_{RR} \) – forces and moments transmitted from the suspension to the body; \( F_a, M_a \) – aerodynamic drag force and moment.

The suspension model considers displacement of the wheel center under forces and moments or torques arising in the contact patch between the wheel and bearing surface. The suspension kinematics, characteristics of elastic and damping elements are described by means of tabular dependences.

The wheel model is based on the work [1] and describes the forces and moments or torques arising in the contact patch between the wheel and the bearing surface taking into account the longitudinal slip coefficient and slip angle. The dependences of the forces and moments on the slip coefficient and slip angle are also described by means of tabular dependences.

The detailed description of the vehicle motion mathematical model being used is provided in papers [2, 3].

The characteristics of the e-machine being used in this model are shown in Figure 1. These characteristics were obtained experimentally in TU Ilmenau.

**Figure 1.** Characteristic curve of e-machine in braking mode.

4. **Algorithm of mixed braking torque control with use of fuzzy logic**

The whole process of the mixed braking control within the anti-lock braking system operation can be divided into several key stages:

1. Determination of the target wheel slip ratio corresponding to the maximum tyre-bearing surface friction coefficient;
2. Setting the braking torque on the e-machine shafts;
3. Setting the pressure in the brake circuits.

The main objective of the mixed braking control algorithm is maintaining the percentage of use or utilization rate of the e-machine braking torque at the specified level. Within the anti-lock braking
system operation, the e-machine braking torque is corrected for the current slip coefficient to correspond to the target value. Upon that, the e-machine loading percentage is adjusted by means of changing the pressure in the wheel brake cylinders.

5. Target wheel slip coefficient determination
Within the paper, the Semmler's method is applied to assess the target wheel slip coefficient. The detailed description of this method is given in article [4]. This method was updated within this paper. The basic differences of the method applied within this paper can be described as follows:

1. At each start of the ABS control algorithm, the last value of the target slip coefficient is memorized;
2. At the ABS actuation, within the first 0.3 second, the target slip is equated to the value obtained from item 1;
3. Within the following 0.55 second, the target slip value is determined based on the vehicle deceleration value;
4. After 0.85 second, the algorithm operates as the original one;
5. If the vehicle deceleration changes by more than ±0.04 m/s², the target slip is determined based on the vehicle deceleration for the next 2 seconds, then based on the expression in item 4.

6. Determination of braking torque on e-machine shafts
The braking torque on the e-machine shafts is set by means of a PI controller. The feedback is performed based on the information on the wheel slip coefficient. The control error is calculated as the difference between the target and current slip coefficients.

7. Determination of pressure in brake circuits
Determination of the target pressure in the brake circuits is performed by means of application of the fuzzy logic control, implemented according to the Mamdani principle. The fuzzy logic system analyzes the e-machines loading percentage and then adjusts the pressure in the brake circuits. In other words, the target pressure value is determined by means of the fuzzy logic, then the pressure in the brake cylinders is corrected by means of the PI controller.

The linguistic variable for the input values of the use degree for the e-machines T torque was divided into five terms. Membership functions µ(x) are shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** Levels of e-machine torque use.

The target pressure (P) levels can be described with five terms; membership functions µ(x) are shown in Figure 3.
In this paper, the level of e-machine torque use matching the "OK" level is the target e-machine loading level. And upon that, adjusting the values of specific levels allows changing the desired target e-machine loading level, which is necessary for taking the state of charge of the battery, its temperature and other important parameters of the vehicle high-voltage system into account.

The combination of the target output pressure is calculated based on rules base:
1. If the percentage of the used torque is "Very low", then the pressure is "Very low";
2. If the percentage of the used torque is "Low", then the pressure is "Low";
3. If the percentage of the used torque is "Ok", then the pressure is "Ok";
4. If the percentage of the used torque is "High", then the pressure is "High";
5. If the percentage of the used torque is "Very high", then the pressure is "Very high";

The target braking pressure is calculated as a projection of the center of gravity of the resulting figure on the X axis shown in Fig. 3.

The pressure in the brake circuits is adjusted via the PI controller. The feedback is performed based on the information on the current braking pressure. A control error is calculated as the difference between the reference value and the current value.

**Figure 3.** Output target pressure levels.

**Figure 4.** Process of braking at 100 km/h.
between the target and current pressure value taking the pressure in the brake master cylinder into account.

An example of system operation during braking at 100 km/h on the surface with the tyre-road friction coefficient of 0.8 is presented in Figure 4. It can be noted that the electric motor loading level corresponds to the target values – the "Ok" level in Figure 2.

8. Virtual test method
The following virtual test conditions were used for evaluation of ABS operation efficiency:

1. Initial speed: 61 and 101 km/h.
2. Wheel and bearing surface friction coefficient: 0.8 and 0.1.
3. When achieving the speeds of 60 and 100 km/h respectively, the brake pedal shall be pressed with the force of 300 N.
4. Upon decelerating to 15 km/h, the test stops.

The developed operation algorithm for the ABS with mixed braking was evaluated in comparison with the algorithm of the ABS using only friction brakes and pressure control by means of the PI controller. The controller error was calculated as the difference between the current and target slip coefficients.

9. ABS operation efficiency evaluation criteria.
The ABS operation efficiency was evaluated by six criteria from paper [5]:

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 characterized by the percentage ratio of the difference between the maximum and minimum wheel angular speeds to the maximum wheel angular speed at the start of ABS operation.
6. ITAE Jerk – integral of the absolute derivative of acceleration multiplied by time.

10. Comparative assessment of anti-lock braking system algorithms operation
Table 2 and Figure 5 show the ABS operation efficiency evaluation indicators when braking at the speed of 60 km/h at the tyre-road friction coefficient equal to 0.8 and 0.1.

Table 3 and Figure 6 show the ABS operation efficiency evaluation criteria indicators when braking at the speed of 100 km/h at the tyre-road friction coefficient equal to 0.8 and 0.1.
Table 2. Summary table of criteria for ABS operation efficiency evaluation when braking at the speed of 60 km/h

| Control variant | Braking distance, m | Average deceleration, m/s² | ABSIP | Average slip, % | Peak-to-peak value, front axle, % | Peak-to-peak value, rear axle, % | Jerk ITAE |
|-----------------|---------------------|-----------------------------|-------|-----------------|----------------------------------|--------------------------------|-----------|
| Mixed braking   | 20.62               | -6.38                       | 1.12  | -18.77          | 6.8                              | 4.61                           | 66.88     |
| Friction braking| 20.79               | -6.3                        | 1.11  | -27.33          | 9.74                             | 16.95                          | 69.19     |
| Without ABS     | 22.84               | -5.69                       | 1.00  | -99.65          | 281                              | 200.8                          | 70.00     |

| Control variant | Braking distance, m | Average deceleration, m/s² | ABSIP | Average slip, % | Peak-to-peak value, front axle, % | Peak-to-peak value, rear axle, % | Jerk ITAE |
|-----------------|---------------------|-----------------------------|-------|-----------------|----------------------------------|--------------------------------|-----------|
| Mixed braking   | 157.3               | -0.82                       | 1.09  | -3.79           | 1.04                             | 0.19                           | 6.91      |
| Friction braking| 164.20              | -0.78                       | 1.04  | -7.56           | 8.66                             | 51.58                          | 122.70    |
| Without ABS     | 171.60              | -0.75                       | 1.00  | -99.96          | 688.4                            | 628.6                          | 36.42     |

Figure 5. Circular radar charts with ABS operation efficiency evaluation indicators when braking at the speed of 60 km/h.

The anti-lock braking system with mixed braking provides better braking performance compared to the braking using only friction brakes.

The braking distance for the speed of 60 km/h on the surface with a high tyre-road friction coefficient decreases by 0.17 meter, which amounts to 0.74%, the average deceleration decreases by 0.08 m/s² (1.41%), the Jerk ITAE decreases by 2.31 (3.30%). The braking distance decreases by 4.02% or 6.90 meters when braking on the surface with a low tyre-road friction coefficient.

The braking distance for the speed of 100 km/h on the surface with a high tyre-road friction coefficient decreases by 0.9 meter, which amounts to 1.4%, the average deceleration decreases by 0.07 m/s² (1.24%), the Jerk ITAE decreases by 19 (99.4%), which means the increase in the level of comfort for the driver and passengers. The braking distance decreases by 2.53% or 11.4 meters when braking on the surface with a low tyre-road friction coefficient. The additional advantage of the mixed braking is the possibility to convert the kinetic energy of the vehicle motion into the electric one.
Table 3. Summary table of criteria for ABS operation efficiency evaluation when braking at the speed of 100 km/h.

| Control variant   | Braking distance, m | Average deceleration, m/s² | ABSIP | Average slip, % | Peak-to peak value, front axle, % | Peak-to peak value, rear axle, % | Jerk ITAE |
|-------------------|---------------------|-----------------------------|-------|-----------------|-----------------------------------|----------------------------------|-----------|
| Mixed braking     | 57.66               | -6.54                       | 1.14  | -19.56          | 0.8                               | 1.8                              | 13.31     |
| Friction braking  | 58.56               | -6.47                       | 1.13  | -26.53          | 51.16                             | 5.45                             | 32.36     |
| Without ABS      | 65.40               | -5.74                       | 1.00  | -98.50          | 138.4                             | 285.7                            | 19.17     |
| Mixed braking     | 415.70              | -0.87                       | 1.08  | -19.56          | 0.8                               | 1.8                              | 13.31     |
| Friction braking  | 427.10              | -0.85                       | 1.06  | -26.53          | 51.16                             | 5.45                             | 32.36     |
| Without ABS      | 450.40              | -0.81                       | 1.00  | -98.50          | 138.4                             | 285.7                            | 19.17     |

Figure 6. Circular radar charts with ABS operation efficiency evaluation criteria indicators when braking at the speed of 100 km/h.

11. Conclusion
Thus, an increase in performance or operation efficiency of the intelligent anti-lock braking system for electric vehicles when using the mixed braking in electric vehicles can be noted. The additional advantage when using such systems is the increase of passenger comfort due to reduction of the slip coefficient oscillation amplitude relative to the target values. Besides, it is possible to recover the kinetic energy during braking, which increases the single charge cruising range. The simplicity of adjustment of the fuzzy logic controller for the changeable parameters of the target level of the electric motor load as well as its wide operating limits shall be mentioned separately.

References
[1] Retrieved from: https://www.strategyand.pwc.com/gx/en/insight/2020/digital-auto-report.html
[2] Gillespie T 1992 Fundamentals of Vehicle Dynamics (Warrendale: PA Society of Automotive Engineers)
[3] Selifonov V 2009 Vehicle Theory (Moscow: Greenlight LLC Publ.)

[4] Bakhmutov S V, Umnitsyn A A and 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 326-333

[5] 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