

Influence of the Tire Inflation Pressure Variation on Braking Efficiency and Driving Comfort of Full Electric Vehicle with Continuous Anti-Lock Braking System

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ABSTRACT

The presented study demonstrates results of experimental investigations of the anti-lock braking system (ABS) performance under variation of tire inflation pressure. This research is motivated by the fact that the changes in tire inflation pressure during the vehicle operation can distinctly affect peak value of friction coefficient, stiffness and other tire characteristics, which are influencing on the ABS performance. In particular, alteration of tire parameters can cause distortion of the ABS functions resulting in increase of the braking distance. The study is based on experimental tests performed for continuous ABS control algorithm, which was implemented to the full electric vehicle with four individual on-board electric motors. All straight-line braking tests are performed on the low-friction surface where wheels are more tended to lock. The experimental results of ABS braking clearly demonstrated impact of different tire inflation pressure levels (1.5, 2.5 and 3.5 bar) on (i) braking performance, (ii) control performance of ABS, and (iii) driving comfort during the panic braking. Conclusions are made on possible ABS adaptability and robustness improvement and its use in combination with active or passive tire pressure systems.

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INTRODUCTION

Interaction between the road and the tire plays the main role in vehicle motion. As soon as the forces in tire-road contact are determined by linear laws, behavior of the vehicle is predictable and, excluding human factors, the driver is assumed to be in potentially safe driving conditions. An emergency driving situation can usually arise in the case of unpredictable vehicle behavior that is caused most of all by a non-linear relation between realized tire-road contact forces and wheel kinematic parameters. For straight-line braking maneuvers, it leads to the significant loss of the braking force and, as consequence, to lower vehicle deceleration and longer braking distance. Overcoming of these critical situations is the main task of anti-lock braking systems, which is aimed to keep the wheel slip ratio in region, where the maximum possible braking forces on the wheels can be realized according to the driver demand.

Nowadays, a wide range of ABS modifications are known and represented by diverse hardware components and control strategies. In particular, classical approaches, where the friction brake system is actuated by the ABS in accordance with rule-based algorithms, are still finding a spread use in commercial anti-lock braking systems. The rule-based ABS is explicitly described in various technical papers and reference books [1, 2]. However, the strengthening of requirements to the vehicle safety and the inclusion of ABS in the control architecture of other automotive systems like Electronic

Stability Control (ESC) causes higher complexity of the control rules and increases the computational load. Hence, despite the high robustness provided by rule-based control approach, it results to a very time consuming procedure of the system tuning.

To enhance the ABS performance and adaptability, nowadays many research groups are seeking for new approaches towards robust ABS control. In this respect the continuous ABS control principle can be considered as one of the efficient solutions, which is confirmed by recent results of its comparative analysis with the rule-based approach [3]. However, the continuous ABS control receives more complexity when actuators of different nature are involved in the braking process. This situation is typical for full electric vehicles (FEV), where the anti-lock braking system uses both the friction brake system and the individual electric motors as actuators. For instance, the example of such ABS architecture is described and experimentally validated for full-electric sport utility vehicle (SUV) in [4].

The performance both of rule-based and continuous anti-lock braking systems depends strongly on the system adaptability. Modern ABS must consider variation of different parameters, such as tire-road friction, vehicle loading, etc. One of the important but rarely explored areas in this regard remains the influence of the tire pressure on the ABS performance. It is experimentally confirmed in [5, 6, 7] that the tire inflation pressure produces the variation in contact forces caused by the changes in longitudinal and lateral stiffness and

the peak value of tire-road friction coefficient. Nevertheless, there is a lack of published comprehensive studies investigating this effect in terms of the vehicle braking process involving the ABS control. In particular, some relevant experimental results were presented by Hadrys et.al. in [8]. It was shown that with initial velocity of 60 km/h the braking distance can vary from 22 meters to 24.6 meters on the dry road and from 25.4 m to about 29 meters on the wet road when changing the tire pressure from 2 to 3 bar on the front axle. The relevant results were also introduced by Marshek et.al. in [9]. This study analyzed the braking performance of five passenger cars and one sport utility vehicle (SUV) equipped with the anti-lock braking system. The results are obtained on the dry tarmac surface with tire pressure variation from 0.69 bar to maximum inflation pressure recommended by the manufacturers for each tested car. Another research performed by the authors of the proposed paper showed that the braking distance can be reduced by 16 meters on wet roads by changing the tire inflation pressure from 2.5 to 5.0 bar [10].

There are also some relevant studies, which were performed on the simulation level and included the tire pressure monitoring systems (TPMS) into the ABS architecture. For example, the combined use of ABS based on PID and fuzzy logic and an indirect tire pressure monitoring system is proposed in [11]. The ABS PID-control gains K_p , K_i and K_d are continuously updated according to the control error e and its derivative. The performed simulations showed independency of brake performance from the tire pressure variation up to 25% in ABS braking mode and robust operation of slip control and tire pressure monitoring in general. The similar approach is used in [12], where the ABS is based on sliding mode control. The results confirmed both required braking performance for different tire pressure levels with up to 20% deflation from initial level and no loss in tire pressure monitoring performance.

Considering aforementioned studies it is important to admit that not only quasi-static tire contact forces, but also tire transient characteristics, are influenced by the tire pressure variation. Therefore, it is not feasible to evaluate adequately the effect of the tire pressure inflation on ABS operation only in simulation environment by involving known tire models in the ABS control loop.

Compared to the aforementioned theoretical and experimental studies the proposed research (i) is aimed on the evaluation of influence of the tire inflation pressure variation on the braking performance, (ii) considers control performance of the developed and implemented anti-lock braking system, (iii) analyzes the driving comfort during panic braking, (iv) formulates recommendations for the ABS adaptability and robustness improvements, (v) provides feasibility study on possible further passive TPMS and ABS integration [11], (vi) sheds the light on feasible ABS and active tire pressure control system (TPCS) integration proposed in [10, 13]. The main outcomes of the study are based on experiments on the road with low-friction surface, where wheels are more tended to lock than in high-friction conditions. The related ABS tests include variation of the tire pressure (1.5, 2.5 and 3.5 bar) for straight-line braking maneuvers.

The proposed manuscript is organized as follows. In the first section (i) the vehicle configuration is specified paying special attention to the brake system and the powertrain design, further (ii) developed

and implemented anti-lock braking system is represented, (iii) for the specified straight-line braking maneuvers experimental investigation is performed, (iv) proposed quantitative performance and comfort criteria are compared for different tire pressures, (v) tire pressure variation influence on the ABS performance is analyzed and (vi) recommendations for the ABS adaptability and robustness improvements are given.

SPECIFICATIONS OF THE TEST VEHICLE

The test vehicle used in the proposed study is the full electric SUV, Fig. 1, developed within the framework of the European project E-VECTOORC [14].



Figure 1. Range Rover Evoque equipped with four individual on-board electric motors and installed measuring hub on front right wheel

The brake system architecture of the test vehicle involves both friction brakes and electric motors. The decoupled electro-hydraulic brake (EHB) system operates the friction brakes for each wheel individually, Fig. 2. The EHB system is provided by TRW Automotive and known on the market as Slip Control Boost (SCB) [15]. The system utilizes the pump and the high pressure accumulator capable to keep the preload pressure up to 180 bar. It ensures quicker system response compared to the conventional brake systems. The electro-hydraulic control unit (EHCU) realizes functions of estimation and control of the brake pressure in each individual caliper.

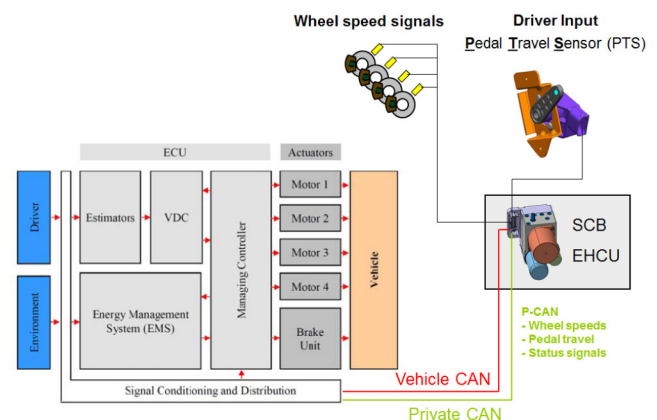


Figure 2. Electro-hydraulic brake system represented by Slip Control Boost developed by TRW Automotive [16]

The electric powertrain is represented by the individual on-board electric motors and the single-speed gearbox with ratio of 1.0:1 through a two stage reduction. It is schematically depicted on Fig. 3

The motors are characterized by peak torque / power of 200 Nm / 100 kW, nominal torque / power of 80 Nm / 35 kW, and maximum speed of 15000 rpm.

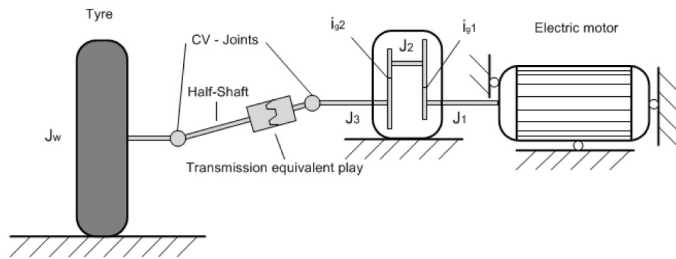


Figure 3. Electric powertrain mounted at each wheel for individual wheel torque control

During the braking process (as well as in traction) the powertrain can produce some oscillations influencing negatively the drivability characteristics of the vehicle and, in particular, slip control functions. Such influence of the powertrain dynamics on the brake functions is presented in [16]. To provide damping functions of the powertrain, the active vibration control (AVC) is developed and embedded into the global vehicle control architecture [17].

The mounted tires at the front and rear axle are Continental Cross Contact 235/55R19 (105V). For analysis of the tire inflation pressure on tire characteristics, such as longitudinal and lateral stiffness and peak friction coefficient, it is required to evaluate forces generated in tire-road contact. To resolve this task a 6-Component Wheel Force Transducer can be used. In the case of investigated vehicle, 19" RoaDyn S635 wheel force sensor developed by Kistler Group is used and installed at the front right wheel (Fig. 1). It makes possible to measure 3 torques and 3 forces with a rotary angle accuracy of approximately 0.1 degree [18].

CONTINUOUS ANTI-LOCK BRAKING SYSTEM

The continuous ABS algorithm realized for the test vehicle is developed for the purpose of wheel slip control in braking mode for different configurations of the brake system. In the presented research the use of friction brake system is minimized. It means that slip control functions are mainly realized by the electric motors, and the friction brakes are gradually involved only in the very low speeds to keep the vehicle in stand still position. The proposed ABS algorithm is schematically represented in Fig. 4 and utilizes the gain-scheduled proportional-integral direct slip control with feedforward and feedback control contributions. Such control strategy is able to provide accurate wheel slip tracking independently from the actual vehicle velocity. As the result, wheels are operating most of the braking time in the extremum area of the tire friction-wheel slip curve, where maximum possible braking forces can be realized. As soon as in this case the longitudinal tire force is kept closely constant during the single braking maneuver, the vehicle deceleration does not suffer from essential oscillations and the driving comfort is significantly improved compared to the conventional approaches.

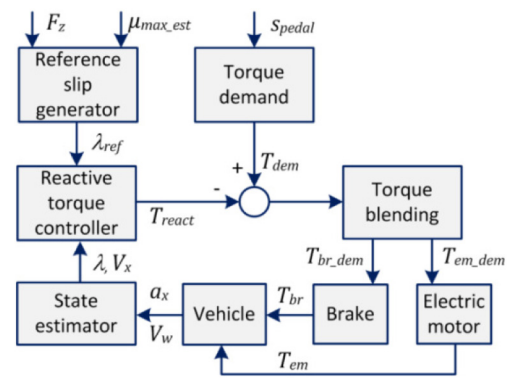


Figure 4. Continuous anti-lock braking system control architecture [4]

According to the scheme on Fig. 4, the brake torque demand T_{dem} for each wheel is generated depending on the driver control action measured as the brake pedal travel s_{pedal} . The brake torque demand is added up with the reactive torque T_{react} computed by the reactive torque controller, which uses the reference wheel slip λ_{ref} , the actual wheel slip λ and the vehicle velocity V_x as input parameters. The reference wheel slip is calculated in the reference slip generator taking into account the wheel loading F_z and the estimated maximum value of the tire-road friction coefficient μ_{max_est} . The resulting torque from T_{dem} and T_{react} is processed in the torque blending block allocating the torque shares for the electro-hydraulic brake system T_{br_dem} and the electric motors T_{em_dem} . These torques are realized by the corresponding actuators, and then the actual torques T_{br} and T_{em} are applied to the corresponding wheels. The wheel slip ratios and the vehicle velocity are observed using the wheel velocities V_w , the vehicle acceleration / deceleration a_x and the actual wheel torque T_w .

More detailed description of the represented continuous ABS is given in [4]. For the purposes of the discussed study, the ABS control logic has been slightly simplified. It is done to avoid any overlap of investigated effects with the ABS adaptation functions. It is in particular assumed that the optimal value of the wheel slip is 5% that has been used as the reference value.

EXPERIMENTAL RESULTS AND ANALYSIS

All the tests are performed on the wet pavement composed from the basalt tiles. The road coefficient of friction varies in the range from 0.2 to 0.3.

Tire Characteristics Measurement

Before performing the main ABS tests with tire pressure variation, it is important to evaluate the pressure influence on tire characteristics such as the longitudinal stiffness and the peak friction coefficient. To obtain typical μ - λ (tire friction-wheel slip) plot, the vehicle is progressively braked from 60 km/h until the full lock of the wheels. Vehicle weight distribution to each wheel was measured in the stand still position and equals to 570 kg for the front right wheel, where the wheel force transducer was mounted. As it can be seen on Fig. 5, tire pressure variation influences noticeably the tire stiffness, the maximum of the longitudinal force maximum and the wheel slip ratio