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RESULTS OF FUNCTIONAL SIMULATION FOR ABS WITH PRE-EXTREME CONTROL

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ABSTRACT–The creation of automotive systems of active safety with intelligent functions needs the use of new control principles for the wheel and automobile. One of such directions is the pre-extreme control strategy. Its aim is the ensuring of wheel's work in pre-extreme, stable area of tire grip wheel slip dependence. The simplest realization of pre-extreme control in automotive anti-lock brake systems consists in the threshold and gradient algorithms. A comparative analysis of these algorithms, which has been made on "hardware in-the-loop" simulation results of the braking for bus with various anti-lock brake systems (ABS), indicated their high efficiency.

KEY WORDS : System of active safety, ABS, Pre-extreme control

NOMENCLATURE

c_t : tire stiffness
$C_{1...3}$: factors of μ-s-curve
H : response function
F_c : control effort on a brake gear
F_z : normal force
F_μ : force within a wheel-road-contact
j : vehicle acceleration/deceleration
J : moment of inertia of a wheel
m : weight reduced to a vehicle wheel
M_{br} : brake torque of the brake mechanism
p : brake pressure
P : power
$Đ_{br}$: dissipative power on brake gear
$Đ_r$: power of rotational wheel movement
P_t : power of translational wheel movement
$Đ_\mu$: dissipative power within tire-road contact
q : microprofile height
r_d : dynamic radius of a wheel
s : wheel slip (sliding)
s_m : maximal value of wheel's sliding achieved by ABS operation
S : braking distance
V : velocity of vehicle
V_s : sliding velocity
α : sideslip angle
δS : relative change of braking distance
$\delta\mu_{br}$: average value of tire grip coefficient during the braking time
Δp : air consumption
ε : angular acceleration/deceleration of a wheel
ζ : wheel's normal displacement
ζ_t : tire deformation
μ : specific force within a wheel-road contact, coefficient of the wheel's cohesion
μ_x : specific longitudinal force within a wheel-road contact
μ_y : specific lateral force within a wheel-road contact
χ : control deviation
ν : frequency
ω : angular velocity of a wheel

ABS : anti-lock brake system
ECU : electronic control unit
TCS : traction control system
VDC : vehicle dynamics control

1. INTRODUCTION

The development of anti-lock brake systems for heavy-duty trucks and buses requires taking proper account of special features:
- Moments of inertia for a wheel and vehicle mass reduced to a wheel are 10–50 times more than the same parameters for cars
- Pneumatic brake drive as the main actuator can ensure the cycle ABS work with relatively small frequency

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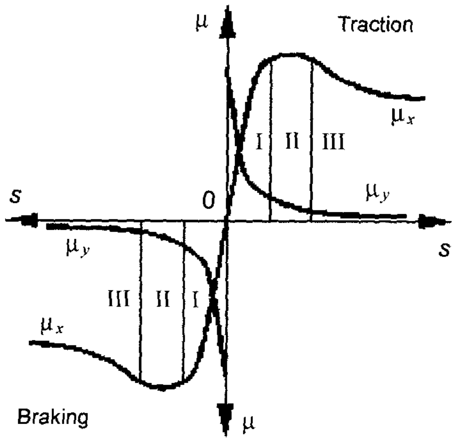

Figure 1. Typical areas of μ-s-curves: *I*-pre-extreme area, *II*-extreme area, *III*-post-extreme area.

(max. 6–8 Hz compared to 15–20 Hz and higher for hydraulic drive)

- Considerable consumption of actuating medium by ABS operation (compressed air at ABS exhaust mode vents to the atmosphere).

These and other factors were being noted in a number of investigations, from the classical works (Neu, 1970; Petersen, 1987; Scholz, 1986), and are constantly taken into account by the development of control principles for ABS.

Now, the generally accepted approach to anti-lock brake systems consists in the use of combined algorithms wherein the wheel slip and derivative from wheel's rotational velocity are the ABS control parameters (WABCO, 1999). However the evolution of intelligent technologies and other systems of active safety (traction control systems TCS, vehicle dynamics control VDC) sends in search of new approaches in this field.

The present work continues discussion about pre-extreme control philosophy for anti-lock braking systems (Ivanov, 2001 and 2002). A special feature of this type of control is the forced ABS work into the pre-extreme area of μ-slip-dependence to provide a high reserve of vehicle stability, Figure 1.

The aim of this investigation is to ascertain the performance capabilities of pre-extreme ABS for city buses and heavy trucks. At the design stage, a decision has been taken to make the comparative analysis for various ABS algorithms using HIL-simulation with original software "Virtual Proving Ground", due to Research laboratory for Integrated Control Systems, Institute for Machine Mechanics and Reliability by National Academy of Sciences of Belarus.

This paper summarizes the gained research results, and describes the procedure for simulation and comparison of ABS algorithms.

2. CONTROL PRINCIPLES OF PRE-EXTREME ABS

2.1. Structure of Pre-extreme ABS

The necessary and sufficient sensor part in the structure of a pre-extreme ABS, Figure 2, includes:

- individual sensors generating information about rotational speed v_i for each wheel
- hardware-based or virtual load sensors to fix the change of weight reduced to a vehicle wheel μ_i pressure transducer to fix the brake chamber pressure δ_i.

Wheel's sliding is defined by way of the reference velocity V_{ref} of a vehicle and its derivative dV_{ref}/dt. The information about tire grip μ, sliding velocity V_s and forces within wheel-road-contact F_μ is estimated simultaneously.

In this scheme the parallel information processing takes place. The main control parameters are wheel's sliding and the force within a wheel-road-contact, which define the thresholds into pre-extreme area of $\mu(s)$-dependence. The double control parameters are settings for the wheel's acceleration and slip, as for ordinary ABS. They ensure the brake control by failure of main (pre-extreme) information channel.

The pre-extreme thresholds are not constant and must be adjusted continuously according to the load redistribution and to the hysteresis of brake system through working pressure p_i in brake actuators. In response to the accepted, corrected decision the electronic control unit defines necessary control effort F_{ci} for each brake gear.

For better definition of pre-extreme control, we shall consider the principles of operation of the threshold and gradient pre-extreme anti-lock brake systems.

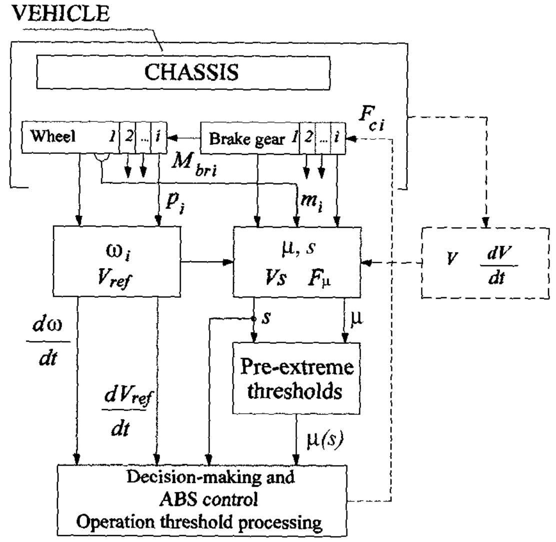

Figure 2. Structure of pre-extreme ABS.

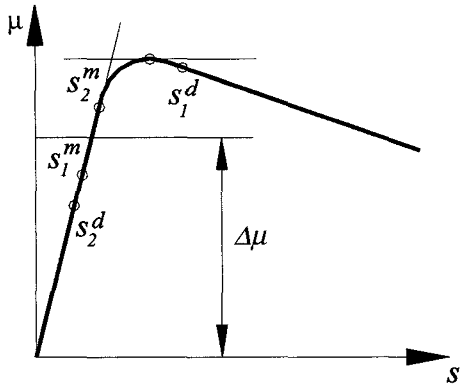

Figure 3. The choice of ABS thresholds.

2.2. Pre-extreme ABS Algorithms (simplified description)

2.2.1. Control principles with thresholds

The choice of thresholds for pre-extreme ABS is shown in Figure 3.

The main threshold s_1^m into the pre-extreme area is selected so that to begin the brake pressure reduction before the extremum of μ–s curve with regard to response time of brake actuators. The main threshold for the next increase of brake pressure s_2^m is selected in such a way that to keep the required level of tire grip efficiency $\Delta\mu$ in one control cycle.

If the main information channel is failed, so the double thresholds come into operation. As a last resort, the emergency threshold s_1^d for brake pressure reduction is so selected that to avoid full slip of a wheel, and the emergency threshold s_2^d for increase of brake pressure to avoid the total brake release.

2.2.2. Gradient control principle

The gradient control principle is based on the assumption that in the pre-extreme field of μ–s curves the initiating, practically linear upgrade of the characteristic takes place. Therefore, the ABS algorithm can use the information about derivative $d\mu/ds$.

The transfer point from linear to non-linear section of μ–s curve can be accepted as a first approximation for the operation threshold of ABS for the pressure exhaust. Such pre-extreme algorithm can be analytically described as follows. ABS applies signal for the pressure release by realization of criterions

$$dF_\mu/ds > 0, \tag{1}$$

and

$$\left|\left(\frac{dF_\mu}{ds}\right)_i - \left(\frac{dF_\mu}{ds}\right)_{i-1}\right| \le \chi_1, \tag{2}$$

where χ_1 is a control deviation for the pressure release. The attainment of value χ_1 is evidence for the completion of linear section of μ–s curve and for the tendency to the approach of an extremum.

The pressure release can begin both in the pre-extreme area and in the post-extreme area of μ–s curve depending on response time of a system. However, the decrease of sliding s will take place in any case. The conditional-branching test for (1) and (2) not occurs in the process and the anti-lock brake system monitors the fulfillment of relations

$$dF_\mu/ds > 0, \tag{3}$$

and

$$\left|\left(\frac{dF_\mu}{ds}\right)_i - \left(\frac{dF_\mu}{ds}\right)_{i-1}\right| \le \chi_1, \tag{4}$$

where χ_2 is a control deviation for the pressure build-up. This deviation indicates that the rating value for displacement from extremum takes place.

The described processes are further repeated until the critical situation comes to end.

For estimation of dF_μ/ds-parameter a virtual sensor can be used. It derives the sought information from signals of wheel speed sensors, brake pressure sensors et al. The determination of dF_μ/ds-signal for a single wheel is realized through braking model based on Koenig's theorem and power balance equation:

$$P_t + P_r = P_{br} + P_\mu \tag{5}$$

or

$$mV\frac{dV}{dt} + J\omega\frac{d\omega}{dt} = M_{br}\cdot\omega + F_\mu(V - \omega\cdot r_d), \tag{6}$$

where P_t is power of translational wheel movement, P_r is power of rotational wheel movement, P_{br} is dissipative power on brake gear, P_μ is dissipative power within tire-road contact.

From (6) the following equation can be deduced

$$\frac{dF_\mu}{ds} = m\frac{dj}{ds} + \frac{1}{r_d}\left(\left(1 - \frac{1}{s}\right)\left(\frac{dM_{br}}{ds} - J\frac{d\varepsilon}{ds}\right) - \frac{M_{br} - (J\cdot\varepsilon)}{s^2}\right) \tag{7}$$

which is placed in the structure of virtual sensor. Here the parameters M_{br}, s, ds, j and ε can be obtained from the wheel speed sensors, brake pressure sensors and accelerometers.

3. TOOLING FOR COMPARATIVE ANALYSIS OF ABS ALGORITHM

3.1. Hardware In-the-Loop Test Bench

For investigation on functional possibilities and comparative

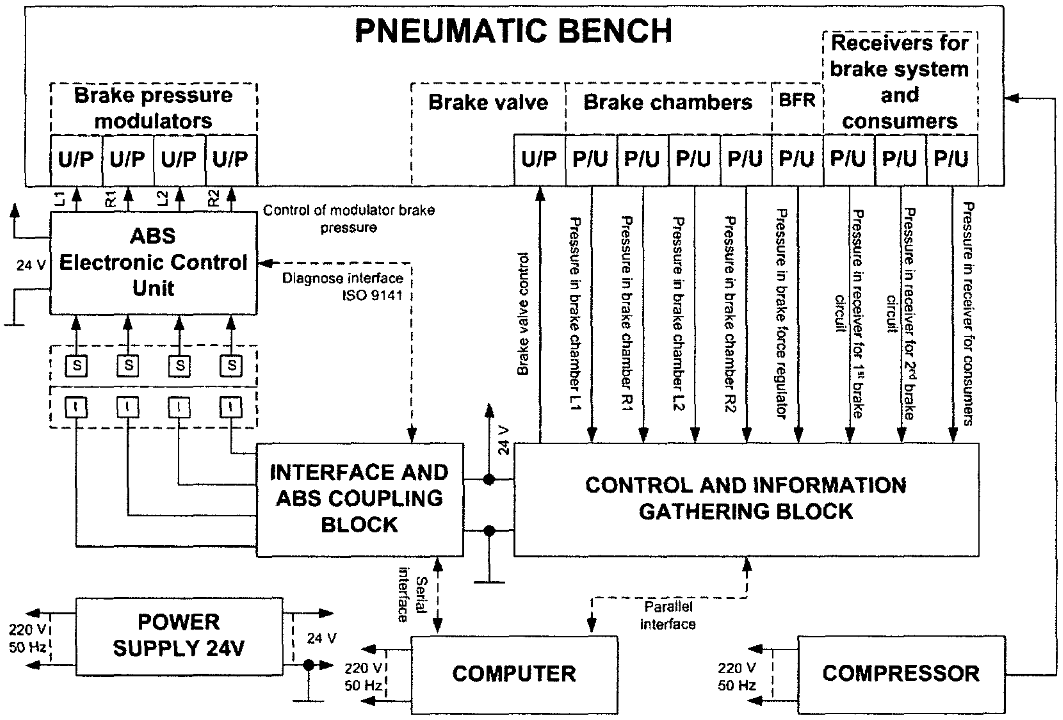

Figure 4. Structure of HILS Test Bench 1-for first brake circuit, 2-for second brake circuit, L-for left wheel, R-for right wheel, BFR-brake force regulator, S-stator of wheel speed sensor, I-imitator of rotational wheel.

analysis of the developed control ABS strategy has been used the technique of Hardware In-the-Loop-Simulation. By the creation of HILS complex under discussion the operation of similar complexes (Bennett, 2002; Ryu, 1998; Zehentbauer, 2001) had been taken into account.

The main tasks of developed HILS, Figure 4, test bench under discussion are:

- Adaptation of ABS algorithms and control parameters to the operation conditions of real electronic control unit (ECU) and pneumatic brake drive of the bus or heavy-duty truck
- Parameter assessment for the common work of pneumatic brake devices and ABS
- Comparative analysis for various algorithms of anti-lock braking systems.

The main components of HILS complex are

- Computer
- Interface and ABS coupling block
- Control and information gathering block
- Pneumatic bench (automotive brake system).

A computer serves for calculation of the braking parameters through internal mathematical model of vehicle and ABS elements as well as for the data receiving and transfer.

The interface and ABS coupling block realizes the interaction between computer and ABS electronic control unit. This block gets information about current wheel's velocities from computer and transforms it in signals of similar nature with waveforms from the real wheel sensors. Also the given block collects and transmits the information about control signals formed in ECU to the computer.

The imitators of rotational wheels and brake pressure modulators ensure the real electrical signals in ECU networks and the correct algorithm processing. The computer can change the ECU settings and read out the diagnostic information through the interface and ABS coupling block with special program according to ISO 9141 standard.

The pneumatic bench corresponds to the real air-operated brake system, and interplays with computer via the control and information gathering block. This HILS-component obtains the signal about the required brake pedal stroke, generates the control impulses for brake valve, gathers and transmits the brake pressure values to computer.

For virtual assessment tests of ABS the special software "Virtual Proving Ground" was being used. This software allows:

- Simulation of systems of active safety for wide spectrum of road conditions
- Joint action with HIL-systems
- Integration of ABS model into the scaled-down bench for the research of electro-pneumatic brake with ABS

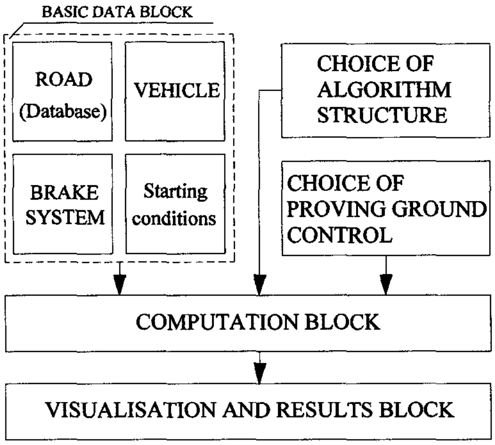

Figure 5. The block diagram of "Virtual Proving Ground".

– Adjustment of ECU functions in ABS.

Figure 5 displays the block diagram of considered software.

The Road Block represents database with the experimental μ-s curves for dry, wet and ice roads by various wheel slip angles and vehicle velocities. The thickness of water film for wet road and the surface temperature for ice road can be chosen. The individual setting of μ-s-dependencies for each vehicle side and the creation of new, hypothetical curves are available.

The Vehicle Block defines the mass and dimensional data of an automobile including the moments of inertia for wheels.

With Brake System Block the user can modify the following parameters:
– Quantum of action for brake drive and ABS
– Actuator dwells
– Response time for brake devices
– Pressure
– Response rate for ABS actuators
– Correcting coefficients due to the kind of brake gear.

The Starting Conditions Block determines a number of other specific parameters like the vehicle velocity for ABS switching-off, initial values for wheel's sliding etc. After generation of complex Basic Data Block the user makes the choice of the ABS algorithm structure.

It is necessary to choice the form of proving ground control immediately prior to simulation. The possibility exists of ABS controlling through model and ECU hardware. If the latter is the case, the ABS control valves are linked with adapters to the computer ports.

3.2. Some Features of Vehicle-road Model for HIL-Simulation

In the described HILS-system the double-truck four-wheel vehicle model (Mitschke, 1990) for movement by non-stationary conditions has been used. This model is supplemented with database for tire-road properties, which includes the data of "tire grip μ-wheel slip s"-dependencies and road surface microprofile.

In the database μ-s curves are described through some factors $C_{1...3}$ (Burkhardt, 1993) and sideslip angle α in the following way:

$$\mu_x = C_1(1-e^{-C_2 \cdot s}) - C_3 \cdot s \tag{8}$$

for linear braking or

$$\mu_x = s_x\left(\frac{C_1(1-e^{-C_2 \cdot s_{sum}})}{s_{sum}} - C_3\right) \tag{9}$$

$$\mu_y = s_y\left(\frac{C_1(1-e^{-C_2 \cdot s_{sum}})}{s_{sum}} - C_3\right)$$

$$= C_1(1-e^{-C_2\sqrt{2(1-\cos_\alpha)}}) - C_3\sqrt{2(1-\cos\alpha)} \tag{10}$$

for curvilinear braking.

In equations (9)–(10) the following parameters are used:

$$s_x = s \cdot \cos\alpha, \tag{11}$$

$$s_y = (1-s)\sin\alpha, \tag{12}$$

$$s_{sum} = \sqrt{s^2 + 2(1-\cos\alpha)(1-s)}. \tag{13}$$

The correction of normal force F_z on single wheel with subject to the microprofile of road surface is realized as follows:

$$F_z = F_z^0 + \Delta F_z, \tag{14}$$

Where F_z^0 is normal force taking into account the load transfer between vehicle axis at braking; ΔF_z is the force increment from fluctuations of unsprung vehicle mass depending on road microprofile:

$$\Delta F_z = c_t(\zeta - q) = c_t \cdot \zeta_t, \tag{15}$$

Where c_t is tire stiffness, ζ is the wheel's normal displacement, q is the microprofile height, ζ_t is the tire deformation.

The following equations can be used for definition of tire deformation by randomicity of road properties. Spectral density of tire deformation dispersion is

$$S\zeta_t(\nu) = S_q^*(\nu) \cdot |H\zeta(i\nu)|^2, \tag{16}$$

Where ν is the frequency, $H\zeta_t(i\nu)$ is the response function of tire deformation.

Normalized mean-square tire deformation is

$$\zeta^*_{t\_n} = \sqrt{2\int_0^\infty 2\zeta^*_n(\nu) \cdot d\nu}. \tag{17}$$

Actual mean-square tire deformation is

$$\zeta_{t\_n} = q_n \cdot \zeta^*_{t\_n}, \tag{18}$$

Where q_n is the mean-square value of ordinate of road microprofile. The obtained value ζ_{t_n} is used in (15).

By means of described procedure the objective model of vehicle-road interaction can be obtained for HIL-simulation.

4. DISCUSSION ABOUT SIMULATION OF PRE-EXTREME ABS ALGORITHMS

4.1. Simulation Object

The city bus (prototype MAZ-104) was selected as simulated vehicle. Its features are accumulated in Table 1.

Simulated environment:

- dry asphalt, braking from 40 and 90 km/h, slip angle 0°, 3° and 6°
- wet asphalt, braking from 90 km/h, water film 1 and 3 mm
- ice, braking from 40 and 90 km/h, surface temperature −0.5 and −8°C
- "mixt" road dry asphalt under left wheels; wet asphalt (water film 3 mm) and ice under right wheels.

The following types of anti-lock brake systems have been chosen for comparative analysis:

- ABS I-simple algorithm with constant wheel's sleep (s=0.1–0.15) as control parameter
- ABS II-combined algorithm with wheel's deceleration and slip as control parameters-conventional type for electro-pneumatic ABS for heavy trucks and buses (WABCO, 1999)
- ABS III-pre-extreme algorithm with thresholds
- ABS IV-gradient pre-extreme algorithm.

For comparison procedure the following factors have been selected:

- braking distance, S, m
- relative change of braking distance as compared to the braking without ABS, δS, %
- maximal value of wheel's sliding achieved by ABS operation, s_m
- average value of tire grip coefficient during the braking

Table 1. Technical data of city bus.

Parameter	Value
Mass of a vehicle, kg	
– total weight	18,000
– laden weight	11,800
Mass distribution on axis, kg	
– by total weight	6,500/11,500
– by laden weight	3,740/8,060
Tires	11/70 R 22.5
Height of center of mass, m	
– by total weight	1.20
– by laden weight	1.25
Wheelbase, m	6.00

Table 2. An example of model output parameters by braking from 90 km/h on "mixt" road (dry asphalt-wet asphalt, 3.0 mm water film).

Laden weight of bus					
ABS	n/a	I	II	III	IV
S, m	83.0	75.9	70.2	71.2	74.4
δS, %	–	8.6	15.4	14.2	10.4
s_m	–	1.00	0.76	0.53	0.1
ν_1, Hz	–	1.6	3.7	3.7	4.1
ν_2, Hz	–	1.1	3.4	2.2	6.3
Δp_1, *bar*	0.381	0.979	0.927	0.897	0.985
Δp_2, *bar*	0.298	0.646	0.381	0.632	0.728
Total weight of bus					
ABS	n/a	I	II	III	IV
S, m	83.7	77.6	72.2	73.8	74.0
δS, %	–	7.3	13.7	11.8	11.6
s_m	–	1.00	0.92	0.46	0.11
ν_1, Hz	–	1.0	1.8	2.2	1.6
ν_2, Hz	–	1.2	4.7	2.9	4.1
Δp_1, *bar*	0.381	0.991	0.941	0.894	0.964
Δp_2, *bar*	0.381	0.810	0.608	0.819	0.851

Table 3. An example of model output parameters by braking from 90 km/h on "mixt" road (dry asphalt-ice, −0.5 °C surface temperature).

Laden weight of bus					
ABS	n/a	I	II	III	IV
S, m	109.9	107.3	103.5	104.8	107.2
δS, %	–	2.4	5.8	4.6	2.5
s_m	–	0.89	0.44	0.38	0.13
ν_1, Hz	–	0.8	1.9	1.4	1.5
ν_2, Hz	–	1.2	2.5	1.9	1.9
Δp_1, *bar*	0.359	0.463	0.377	0.453	0.481
Δp_2, *bar*	0.284	0.334	0.222	0.345	0.348
Total weight of bus					
ABS	n/a	I	II	III	IV
S, m	116.3	115.3	112.4	112.6	114.0
δS, %	–	0.9	3.3	3.2	2.0
s_m	–	0.54	0.58	0.36	0.13
ν_1, Hz	–	0.4	0.7	0.7	0.5
ν_2, Hz	–	1.3	1.5	2.2	1.8
Δp_1, *bar*	0.360	0.452	0.311	0.419	0.454
Δp_2, *bar*	0.360	0.378	0.262	0.420	0.430

Table 4. An example of model output parameters by braking from 90 km/h on wet asphalt, 3.0 mm water film-aquaplaning.

Laden weight of bus					
ABS	n/a	I	II	III	IV
S, m	195.7	150.4	128.8	128.5	134.7
δS, %	–	23.4	34.2	34.3	31.2
s_m	–	1.00	0.92	0.52	0.08
$\delta\mu_{br}$, %	0.593	0.737	0.876	0.902	0.872
Δp_1, bar	0.381	1.481	1.206	1.170	1.029
Δp_2, bar	0.324	1.566	0.684	1.531	1.033
ν, Hz	–	1.2	3.3	3.5	5.3
Total weight of bus					
S, m	196.0	151.8	128.0	128.1	132.5
δS, %	–	22.6	34.7	34.6	32.4
s_m	–	1.00	1.00	1.00	0.11
$\delta\mu_{br}$, %	0.593	0.741	0.886	0.894	0.875
Δp_1, bar	0.381	1.901	1.767	1.468	1.737
Δp_2, bar	0.381	1.960	0.970	1.778	1.824
ν, Hz	–	1.2	4.0	3.1	5.0

Table 5. An example of model output parameters by braking from 40 km/h on dry asphalt, 6° sideslip angle.

Laden weight of bus					
ABS	n/a	I	II	III	IV
S, m	12.6	12.5	12.6	13.0	12.8
δS, %	–	0.8	0.0	-3.2	-1.6
s_m	–	1.00	1.00	0.24	0.29
$\delta\mu_{br}$, %	0.810	0.823	0.813	0.784	0.798
Δp_1, bar	0.358	0.291	0.411	0.490	0.448
Δp_2, bar	0.266	0.200	0.305	0.346	0.319
ν, Hz	–	1.9	3.0	4.4	4.4
Total weight of bus					
S, m	13.4	13.6	13.5	13.5	13.5
δS, %	–	-1.5	-0.7	-0.7	-0.7
s_m	–	0.53	0.95	0.50	0.34
$\delta\mu_{br}$, %	0.775	0.757	0.765	0.769	0.765
Δp_1, bar	0.360	0.446	0.450	0.447	0.445
Δp_2, bar	0.358	0.417	0.413	0.419	0.413
ν, Hz	–	2.1	2.0	2.0	2.7

time, $\delta\mu_{br}$, %
– *air consumption in the brake circuits*, Δp, MPa
– ABS work frequency, ν, Hz.

4.2. Analysis of Simulation Results

The examples of output parameters by simulation of extreme braking are given in Tables 2–5, where Δp_1 and Δp_2 is the pressure reduction in the front and rear brake circuits by the time of the full stopping. In addition for braking on the "mixt" road the ABS work frequency ν_1 and ν_2 are given for the left and right side of vehicle. As results of performed simulations, the following resume can be made.

4.2.1. Brake distance and realization of tire grip coefficient

On dry surface all algorithms ensure the reduction of brake distance except the braking with the high value of slip angle (6°). In the latter case the small increase within the limits of requirements of ECE 13 Regulations is observed.

On wet surface all algorithms bring out the appreciable reduction of brake distance, on the average, about 30–40%.

For ice surface the single case of brake distance increase on 1% was observed for the gradient pre-extreme algorithm. Otherwise each ABS reduces the brake distance no less than 5%.

The obtained average values of tire grip coefficient during the braking time $\delta\mu_{br}$ are comparable for all systems. The maximal magnitudes (> 0.9) were being registered for the ice road by surface temperature in –0.5 °C.

The least values of $\delta\mu_{br}$ showed the ABS I with wheel's sleep as control parameter.

4.2.2. Wheel's sliding

By comparison of ABS the best simulation results were been observed by the pre-extreme algorithms.

For the most critical situation the values of s_m fall in the range:

ice surface
0.06-0.13 for ABS IV
0.23-0.50 for ABS III
0.44-0.92 for ABS II
until *1.00* for ABS I
wet surface
0.08-0.18 for ABS IV
0.12-0.52 for ABS III
0.54-0.92 for ABS II
until *1.00* for ABS I.

4.2.3. ABS work frequency and air consumption

These factors allow to estimate the compatible operation for the ABS and actuator part of a brake system. On the one hand, higher frequency increases the adaptation features of ABS and on the other hand, the frequency is limited by working medium in brakes. The conventional pneumatic brake drive can guarantee the frequency in 6–8 Hz in the limiting case.

The maximal values of ABS work frequency are

comprised:
2.1 Hz for ABS I
5.1 Hz for ABS II
4.4 Hz for ABS III
5.7 Hz for ABS IV.

In most simulated situations both pre-extreme ABS caused slightly higher air consumption in relation to other algorithms. However the residual pressure was within the mark set up by the regulating documents.

4.2.4. Braking on "mixt" road
By braking on the "mixt" road the following principal results were been obtained:
brake distance reduction, %
0.9-8.6 for ABS I
3.3-15.2 for ABS II
3.2-14.2 for ABS III
2.0-11.6 for ABS IV
maximal values of s_m
0.89 for ABS I
0.92 for ABS II
0.53 for ABS III
0.13 for ABS IV.

Therefore, the HILS-Simulation verifies the high functionality of pre-extreme algorithms in comparision with other ABS algorithms under discussion. They can guarantee higher stability reserve, because do not permit the rolling of a wheel in the field of high sliding (parameter s_m), by comparable results for the brake efficiency.

5. CONCLUSION

The simulation of pre-extreme anti-lock brake systems verifies their high functionality. The choice of specific structure for pre-extreme ABS depends primarily on characteristic properties of a vehicle as a control object for system of active safety.

The obtained results allowed to work up the alternative approaches to the design of perspective ABS for heavy trucks and buses. The authors create the concept of stage-by-stage development for pre-extreme ABS. We plan to expound this research in next papers.

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