

Verification of ABS Models Applied in Programs for Road Accident Simulation

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ABSTRACT

The objective of the paper is to present the results of verification of ABS models applied in PC-Crash and HVE (Human-Vehicle-Environment) computer programs in various road conditions. The aim was reached by comparison of the road tests results obtained and calculations performed using the programs for the same initial values of the measured variables. First static tests were carried out for parametrization of the mathematical model of the object of the research - a passenger car equipped with ABS. Road tests were performed including extreme braking on a μ -split with and without corrective steer, and extreme braking during lane-change maneuver.

INTRODUCTION

The function of ABS (Anti-lock Braking System, Antiblockiersystem) is to prevent vehicle wheels locking during braking, in order to maintain steerability and stability of movement. This function is fulfilled by controlling the braking forces of particular wheels so that the optimum longitudinal and lateral slips of wheels are maintained. [1, 2, 3].

ABS, obligatory equipment of newly produced passenger cars nowadays, significantly contributes to the improvement of traffic safety. However, reconstruction of an accident in which a car equipped with ABS was involved is more difficult due to the lack of traces of locking. To help the process of reconstruction various computer programs for the simulation of vehicles movement are used such as: HVE [4], PC-Crash [5], CARAT [6], Cyborg Idea V-Sim [7], Virtual Crash [8].

The accuracy of simulated vehicle movement in the phase of extreme braking is greatly affected by the ABS model. However, it is not practical to include the actual, individual algorithms used in different cars. This is why in these programs universal algorithms are used whose task is to meet general criteria of ABS operation in order to solve the majority of typical problems that appear in road accident analysis.

The study of publications on road accident simulation programs has proved a lack of research into quantitative and qualitative verification of models of the dynamics of motion of ABS equipped vehicles in extreme braking on a μ -split or during lane change maneuver.

The present paper deals with the verification of ABS models used in PC-Crash and HVE programs.

ABS ALGORITHMS IN PC-CRASH PROGRAM

In mathematical modeling of tire-road interaction in PC-Crash program in the conditions of car steady and transient motion two optional models of tire can be used: linear and non-linear TMeasy. In formulas from (1),(2),(3),(4),(5),(6),(7),(8),(9),(10),(11),(12) and in Figures 1,2,3 differentiation of a particular wheel with i was disregarded, however, it should be assumed that each factor refers to i -th wheel. Taking into account two different tire models, the operation of antilock system has been described with different relations, characterized below.

TIRE LINEAR MODEL

In [Figure 1](#) the characteristics of lateral reaction of road on the wheel F_Y (i.e. tire lateral force), which is linearly dependent on slip angle α

$$F_Y = \mu \cdot F_Z \cdot \frac{\alpha}{\alpha_{\max}}, \quad (1)$$

have been presented, where:

- μ – coefficient of adhesion between tire and road (coefficient of friction),
- F_Z – dynamic vertical reaction of road on wheel,
- $\alpha_{\max}$ – slip angle, at which the lateral force of non-braked wheel reaches the maximum value of $F_{Y \max}$.

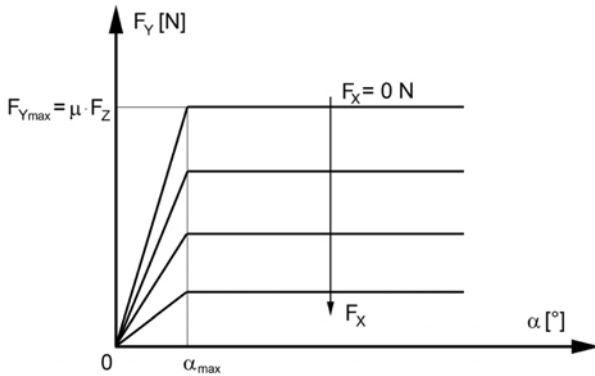


Figure 1. Dependence of lateral force on slip angle (with force F_X as a parameter), in tire linear model

After $\alpha_{\max}$, has been exceeded, force F_Y is constant and is

$$F_{Y \max} = \mu \cdot F_Z. \quad (2)$$

The characteristics can be modified by the user by changing the value of $\alpha_{\max}$, the standard of which is 10° .

In the ABS model based on the tire linear model, first the road lateral reaction on the wheel is calculated, using the slip angle

$$F_Y = -\mu \cdot F_Z \cdot \frac{\alpha}{\alpha_{\max}}. \quad (3)$$

Next, the longitudinal force is restricted to the value

$$F_X = -\sqrt{(\mu \cdot F_Z)^2 - F_Y^2}. \quad (4)$$

ABS, however, cannot make braking forces disappear completely, which could happen in, for instance, entering the turn at a speed exceeding the boundary value and the driver undertaking violent braking. The algorithm, then, guarantees that the braking force will not be reduced below the minimum value, which constitutes 60% of the tangent force available:

$$F_{X \min} = -0.6 \cdot \mu \cdot F_Z, \quad (5)$$

that is, if

$$F_X > F_{X \min}, \quad (6)$$

then

$$F_X := F_{X \min}. \quad (7)$$

The lateral reaction is given by

$$F_Y = -\text{sign}(\alpha) \cdot \sqrt{(\mu \cdot F_Z)^2 - F_{X \min}^2}. \quad (8)$$

TIRE TMEASY MODEL

It is a semi-empirical model, which makes approximation of real forces and moments generated by the tire possible, on the basis of experimental characteristics of tired wheel slip [9]. It is valid for tire tread vibration frequency not exceeding about 8 Hz, and so well fits the class of phenomena that are commonly analyzed in road accident reconstruction [10, 11].

The TMeasy model has been simplified in PC-Crash as compared to the model presented in the quoted reference item, by including only two characteristics of longitudinal reaction, dependent on longitudinal slip, and lateral reaction, dependent on lateral slip.

The characteristic shown in [Figure 2](#) illustrates the unitary longitudinal force of the wheel μ_X , i.e. force F_X related to tire normal loading F_N , depending on longitudinal slip s_X

$$\mu_X(s_X) = \frac{F_X(s_X)}{F_N}. \quad (9)$$

The characteristic shown in [Figure 3](#) is the unitary lateral force μ_Y , i.e. force F_Y referred to normal loading F_N , as a function of lateral slip s_Y

$$\mu_Y(s_Y) = \frac{F_Y(s_Y)}{F_N} \quad (10)$$

To describe the characteristic of the longitudinal force five parameters are sufficient:

$F_{X_{max}}$

maximum unitary longitudinal force,

$s_{X_{max}}$

longitudinal slip at which $F_{X_{max}}$, occurs,

$F_{X_{sl}}$

unitary longitudinal force in wheel full sliding,

$s_{X_{sl}}$

longitudinal slip, when exceeded the longitudinal force will reach constant value of $F_{X_{sl}}$,

$\frac{dF_X}{ds_X}|_0$

initial inclination (cornering stiffness).

An analogous set of five parameters is required to approximate the characteristic of lateral force.

In the ABS algorithm for TMeasy tire model, wheel longitudinal slip is used [12]. If

$$s_X > s_{X_{max}}, \quad (11)$$

then ABS will reduce the corresponding braking force F_X'' following the dependence

$$F_{X''} = \min\{0.6 \cdot F_B, 0.6 \cdot \mu \cdot F_Z\}, \quad (12)$$

where: F_B - given braking force (proportional to the level of brake pedal pressure).

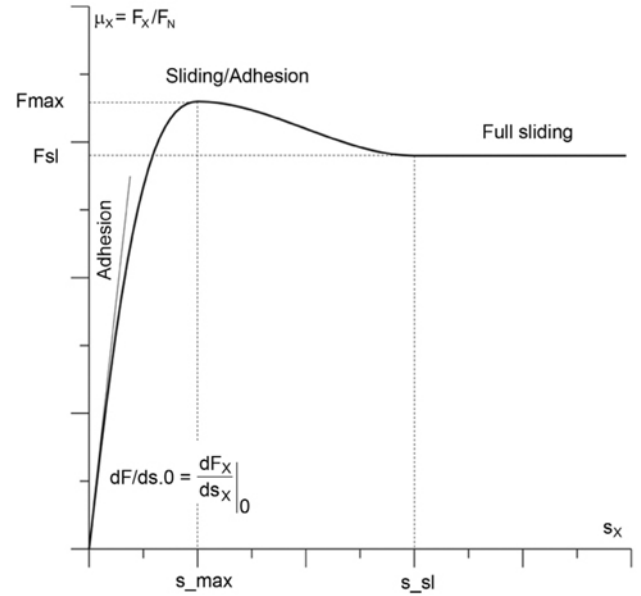


Figure 2. Unitary longitudinal force as a function of tire longitudinal slip

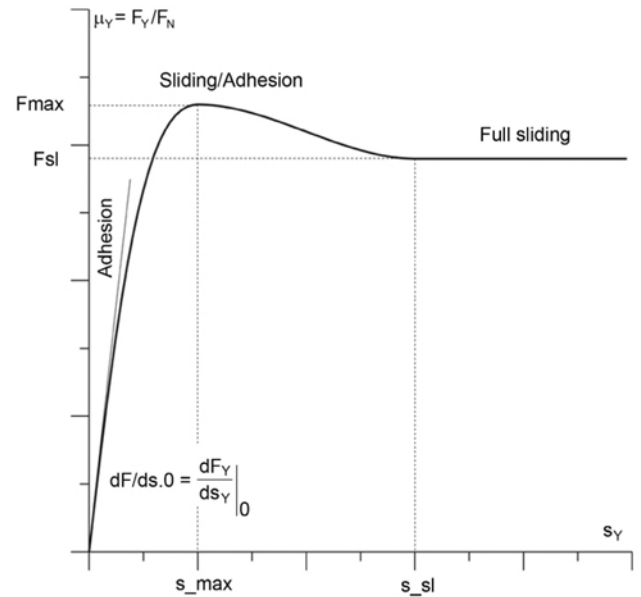


Figure 3. Unitary lateral force as a function of tire lateral slip

After slip has been reduced below $s_{X_{max}}$, ABS will allow again the full braking of the wheel.

ABS model in PC-Crash has been considerably simplified as related to the real construction. It guarantees compared the wheels will not lock simply by adjusting the braking force of each wheel according to the individual friction at each wheel location.

It does not realize the select-low principle, the function of which is to prevent skidding during μ -split braking. The idea is that during violent braking on a surface of different friction under the wheels of the right and left sides of the car, the braking forces of the rear wheels are reduced according to the wheel that moves on the surface of lower friction. Consequently, the vehicle stability is improved, but at the cost of braking distance length. Other algorithms were also disregarded in the program (eg. GMA - Giermomentaufbauverzögerung, yawing moment buildup delay [1, 3]) which are an element of the logic of real ABS operation.

In the case of both the linear and TMeasy ABS algorithms the default time of the system operation cycle is 0.1 s and can be modified by the user. It is, however, an equivalent parameter characterizing the ABS model used in the program, and must not be associated with either the time of wheel angular velocity sampling (by means of toothed disc) or the period of brake fluid pressure modulation.

ABS ALGORITHMS IN HVE PROGRAM

In HVE program two ABS algorithms are available: Tire Slip (TS) and HVE Bosch Version 1, which were described in detail in [19]. The program enables the selection of an ABS algorithm and input variables required in calculations for the selected algorithm.

TIRE SLIP ALGORITHM (TS)

The algorithm guarantees keeping the wheel longitudinal slip in the range from below 5 % to 5 % above the maximum value of the friction coefficient. When the vehicle is braked, the input pressure is controlled by the ABS algorithm on the basis of the instantaneous slip. When the wheel slip is lower or equal to the lower boundary value, the ABS control is off, and the output pressure is equal to the input one. When ABS is on, and the input pressure begins to drop, the output pressure will become equalized and ABS control will be turned off. If, however, the input pressure is constant or rises, the output pressure is kept at the constant level during control, to next increase according to the adopted speed of buildup. When the wheel slip is within the optimum slip range, the output pressure control, shown in Figure 4, will run according to ABS cyclic operation.

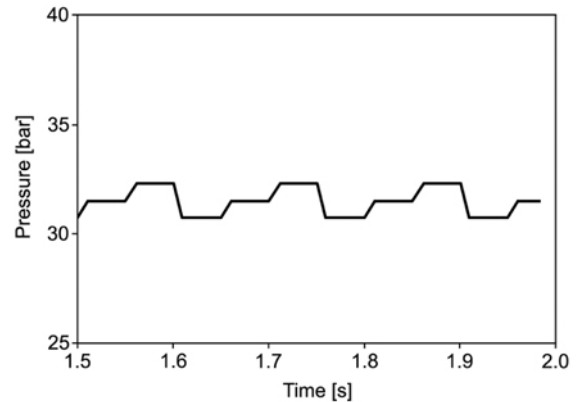


Figure 4. Typical pressure control cycle used in the HVE algorithm based on longitudinal slip control

If the wheel slip is larger than or equal to the maximum slip value, the output pressure, similarly, is kept at a constant level during the control period, after which it is reduced according to the adopted speed (i.e. Release Rate).

HVE BOSCH VERSION 1 ALGORITHM

HVE Bosch 1 algorithm is based on Bosch ABS Version 1 algorithm, described in, among other sources [1, 3], and applies only to passenger cars. The idea of its operation is to analyze the wheel angular acceleration and boundary values of sliding during braking. In HVE program the algorithm has been slightly modified (hence the name HVE Bosch). Output pressure control is divided into eight phases, similarly as in the Bosch ABS algorithm. The differences in pressure control in the two algorithms are shown in Figure 5 and have been discussed in [19].

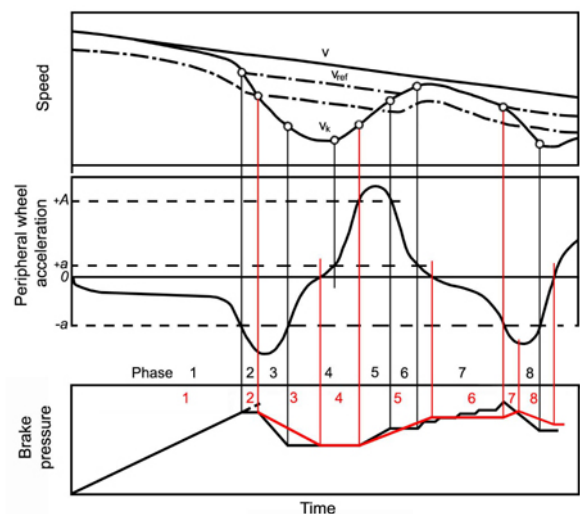


Figure 5. Pressure control in Bosch ABS and HVE Bosch 1 algorithms

AIM AND SCOPE OF THE PAPER

The aim of the paper was to verify mathematical models of ABS used in PC-Crash and HVE programs. Bench tests and on-road experiments were carried out on a passenger car equipped with ABS, in which violent braking was performed under various road conditions. Next, simulations were performed, and the results were compared with those obtained in experiments.

OBJECT OF TESTS

The object tested was an Opel Astra Classic passenger car equipped with ABS, which operated according to select-low (SL) strategy. The car had Michelin Energy XH1 195/55 R 15 tires.

BENCH TESTS

The aim of the bench tests was parametrization of the car's model in the simulation programs. These included determination of:

- center of gravity (CG) location in 3D,
- moments of inertia about the vertical, longitudinal and lateral axes,
- characteristics of suspension stiffness and shock absorber damping,
- steering system stiffness,
- steering ratio.

The recorded results were processed by means of software developed by the Institute of Automotive Vehicles and IC Engines of the Cracow University of Technology [13].

The data determined in bench tests and adopted for calculations in both programs have been listed in Table 1.

Table 1. Technical data of tested car

Variable	Value
Vehicle mass	1260 kg
Distance of CG from front axle	1.149 m
CG height	0.536 m
Steering system ratio	24:1
Stiffness coefficient of steering system	13.88 Nm/rad
Stiffness coefficient – front suspension	20680 N/m
Stiffness coefficient – rear suspension	18000 N/m
Damping coefficient – front suspension	3023.24 Ns/m
Damping coefficient – rear suspension	2200.59 Ns/m
Moment of inertia – roll	438 kgm ²
Moment of inertia – pitch	1475 kgm ²
Moment of inertia – yaw	1913 kgm ²

ROAD TESTS

The road tests covered car movement on a straight and curvilinear track. During movement in a straight line, track tests were performed via emergency braking on a μ -split, in

two versions: with track correction and without counter steer. In the tests on a curvilinear track, extreme braking during a lane-change maneuver was tested.

The road tests were performed on a flat and horizontal section of a concrete surface in summer conditions. To simulate the slippery part of μ -split, PVC 'carpet' was used, 1.5 m wide and 30.0 m long. After the 'carpet' was treated with a mixture of water and soap, the coefficient of friction was 0.34. The average value of the friction coefficient of the concrete surface was 0.73.

Friction coefficient of the concrete surface was established based on series of braking tests of the tested car with four wheels locked (i.e. all wheels on the concrete surface, ABS off, all wheels locked). The same procedure were applied for the 'carpet'. For establishing the acceleration the Crossbow DMU-FOG (direct measurement of acceleration) and Correvit Corrsys® S-CE gauge head (indirect establishing of acceleration based on numerical differentiation of obtained velocity [13]) were used.

On the road surface so prepared the car was braked from the speed of about 50 km/h. The driver engaged the braking system violently when the right wheels were on the 'carpet'. The same driver, well experienced in road tests, guaranteed good repeatability of delay buildup time in all the braking tests.

The braking tests during a single lane change maneuver were performed on a wet concrete surface, at the average friction coefficient of 0.72. The track for the lane change, shown in Figure 6, was laid following the recommendations of norm project BN-90/3615- /06 [14], the aim of which was to determine the properties of a passenger car in by-passing an unexpected obstacle on a road straight section. Having run up the car to the speed of 80 km/h, the driver started extreme braking before changing the movement direction, and continued until he stopped the car.

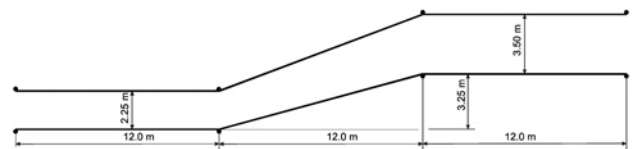


Figure 6. Lane change trajectory after norm BN-90/3615- /06 adopted in tests

In each test the following values were measured:

- linear and angular velocities,
- linear acceleration,
- steering wheel angle,
- wheel angular speeds,
- pressure in braking system.

In total 17 parameters of tested vehicle movement were recorded [15]. After each braking test the car final position was photographed, as shown in Figure 7. Video recording made it possible to show the lateral position of the car at the beginning of movement (Figure 8).

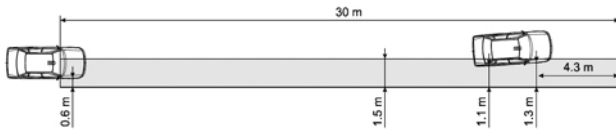


Figure 7. Position of car during entering the μ -split and after stopping



Figure 8. The car position when driving onto μ -split

TESTING EQUIPMENT

In Table 2 the parameters of devices and sensors used in the road tests have been shown. The measurement system was prepared using measurement devices of the Institute of Automotive Vehicles and IC Engines, Cracow University of Technology, and 'Bosmal' R&D Center in Bielsko-Biala.

SIMULATIONS

In each program the following maneuvers were simulated:

- straight-line braking on μ -split with track correction as shown in Figure 9,
- straight-line braking on μ -split without counter steer (in Figure 10 it can be noticed that road wheel steer angular rotations are negligibly small),
- braking during lane change maneuver on wet concrete road surface.

Table 2. Measurement unit used in road tests

Measurement device	Parameter	Measurement range	Measurement precision
Correxit Corrsys® S-CE gauge head	Longitudinal velocity	0 to 97 m/s (0 to 350 km/h)	0.03 m/s
	Lateral velocity	± 62 m/s (± 225 km/h)	0.03 m/s
Measurement apparatus Crossbow DMU-FOG	Acceleration: longitudinal, lateral, vertical	$\pm 2g$	$\pm 30mg$
	Velocities: yawing, pitching, roll	± 260 deg/s	± 0.1 deg/s
Incremental encoder Fritz Kübler GmbH	Steering wheel angle	± 2000 mm	0.5 mm
Wheel rotation sensors	Rotational speed	1000 imp/rev	20 imp/rev
Pressure transducers K-P8AP-231 Hottinger Baldwin Messtechnik GmbH	Pressure in braking system	200 bar	± 2 bar

The results of all the calculations have been given in the Appendix, while in sections 'Simulations in PC-Crash' and 'Simulations in HVE' some examples have been shown.

COMMON DATA ADOPTED IN ALL SIMULATIONS

In all the simulations, in both PC-Crash and HVE, an identical set of essential data, resulting from measurements and shown in Table 1, has been adopted. The time histories of mean front wheel steer angle recorded in road tests was approximated by linear functions, as shown in Figures 9, 10 and 11, concerning the braking tests:

- on μ -split with steering wheel angle correction,
- on μ -split without counter steer,
- during lane change maneuver, respectively.

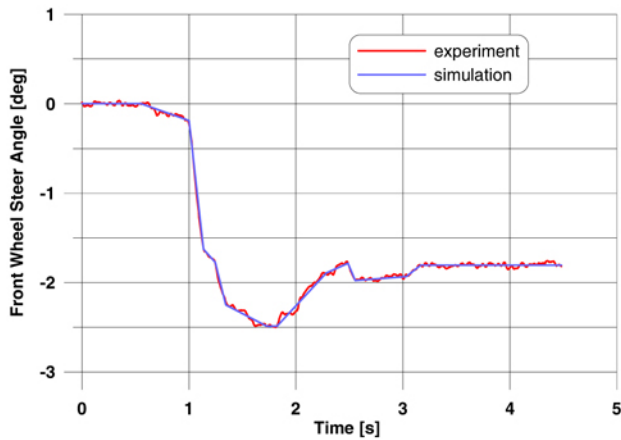


Figure 9. Measured and approximated front wheel steer angle during braking on μ -split with steering wheel angle correction

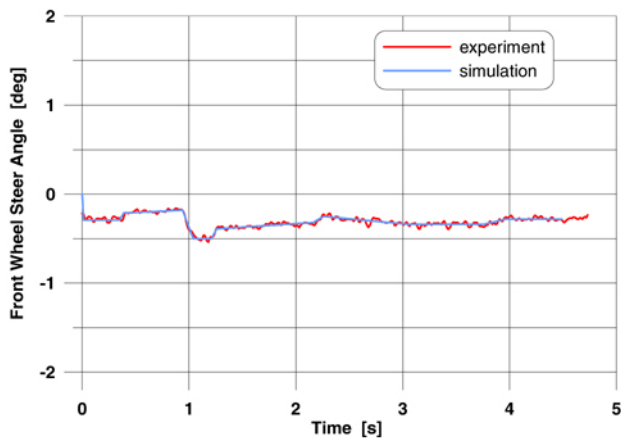


Figure 10. Measured and approximated front wheel steer angle during braking on μ -split without counter steer

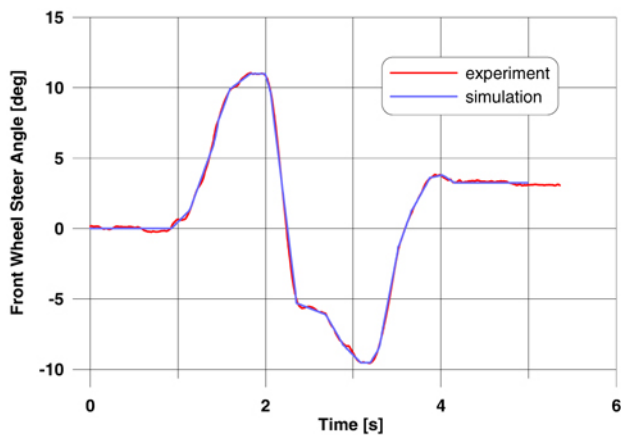


Figure 11. Measured and approximated front wheel steer angle during lane change maneuver

The initial conditions such as CG coordinates, yaw angle, vehicle speed and the moment of braking start were

determined on the basis of the velocities and accelerations recorded during tests. The other data, specific for each program, were adopted by default. The data that had to be modified were presented in the sections that follow.

SIMULATIONS IN PC-CRASH

Vehicle movement was simulated in PC-Crash 8.2 for two tire models: linear and TMeasy. In the first case both default characteristics and characteristics modified by reducing the maximum slip angle (i.e. increasing lateral stiffness of tire) from default 10° to 4° were adopted.

For TMeasy model the simulation was limited to default characteristics only because PC-Crash does not have a database of real tire characteristics. The set of the parameters are listed in the [Table 3](#).

Table 3. Parameters of the tire for the TMeasy tire model; notation - see [Figures 2 and 3](#)

Parameter	Longitudinal Force	Lateral Force
dF/ds.0	15.0	15.0
Fmax	1.1	1.1
s_max	0.21	0.21
Fsl	1.0	1.0
s_sl	0.50	0.50

The ABS of the tested car operated according to SL strategy, which was not included in the model applied in PC-Crash. This is why the control was performed by manual correcting of longitudinal forces of the rear wheels. The method of the correction could be explain on the example of braking simulations on μ -split, illustrated in [Figure 14b](#) and [c](#) (more about this simulation below). First the simulation without correction, shown in [Figure 14b](#), was performed. Time histories of the rear tire brake forces were shown in [Figure 12](#). Next the second simulation was performed in which the *Brake Factors* of the rear left wheel (in the sections *Deceleration* defined in the dialog box *Sequences*) were reduced to achieve the similar level of rear tire brake forces, as shown in [Figure 13](#).

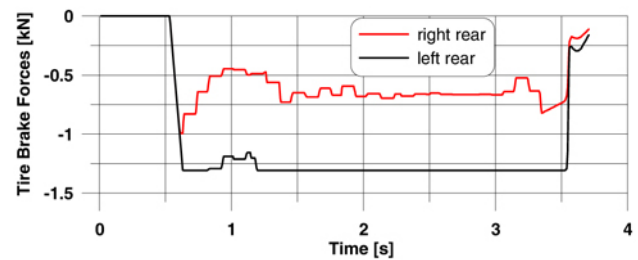


Figure 12. Time history of tire brake forces for simulation shown in [Figure 14b](#) (without select-low)

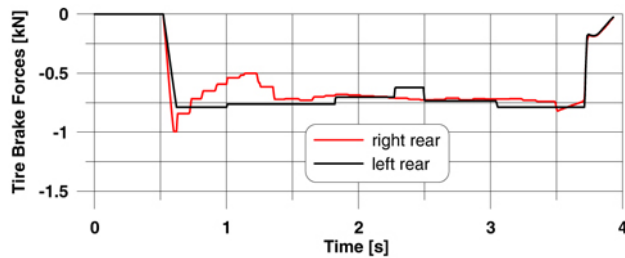


Figure 13. Time history of tire brake forces for simulation shown in Figure 14c (with select-low)

To check the effect of integration step on the accuracy of the simulation results, simulation calculations were done for two boundary values: 5.00 ms (default value in the program) and 0.01 ms.

For each simulated braking test the following characteristics were adopted:

- for tire linear model, default, modified and modified with SL control,
- for tire TMeasy model, default and default with SL control.

Figures 14,15,16,17,18,19 present the results of sample braking simulations on μ -split and during lane change maneuver, together with time histories of longitudinal and lateral acceleration and yaw velocities, which were compared with those measured in experiments. Figures 14, 16 and 18 illustrate the simulated movement trajectory, vehicle position at the beginning of the movement and, for comparison, actual final position.

The results of the other simulations have been included in the [Appendix](#).

All the curves of time histories of lateral acceleration, in simulation on a tire linear model, show a large amplitude of the acceleration. The effect does not depend on integration step (i.e. a smaller step does not level out the curve). Neither is it caused by using Euler's method for numerical integration of motion. It appears when the maximum slip angle has been reduced from default 10° to 4°, which means the tire lateral force characteristic becomes stiff.

In the vehicle dynamics model the mechanisms of the actual suspension have been disregarded, which makes the wheels shift only along the vertical axis perpendicular to the body, while the longitudinal and lateral forces are transmitted onto the body directly, with no filtering. This can lead to a suggestion that this generates sudden lateral acceleration steps, which is supported by correct mean values of these accelerations and attenuated curves of other motion parameters (yaw velocities, and in particular, body yaw and displacement angles in x , y , z directions) [16].

SIMULATIONS IN HVE

The simulations were performed in SIMON program (SIMulation MOdel Non-linear) [17, 18], which is a part of the HVE package. Two algorithms of ABS operation have been used: TS and HVE Bosch [19]. Default moments of wheel inertia and generic tire characteristics 195/55 R 15 have been adopted. For both algorithms the *Axle-Based Control Method* has been applied.

In case of TS algorithm standard values characterizing its function have been kept; the data adopted for the HVE Bosch algorithm have been given in Table 4. In this case it was necessary to modify the values of *Wheel Spin Acceleration Min.* and *Max.*, default values of pressure modulation rates, however, have been maintained.

Model HVE Bosch is strictly connected with the dynamics of the wheels and braking system and for each vehicle needs an adjustment of these parameters. The default value of *Output Time Interval* has been reduced to 0.01 s. The results of simulation have been shown in [Figures 20,21,22,23,24,25](#).

Table 4. ABS parameters used for HVE Bosch 1 model

Variable	Value
Algorithm	HVE Bosch Version 1
Control Method	Axle-Based
Min Pressure for ABS	68.95 kPa
Min Velocity for ABS	6.44 km/h
Low Friction Threshold	0.47
Delay Method	Axle-Based
Apply Delay	0.05 s
Primary Application Rate	34473.8 kPa/s
Secondary Application Rate	3447.4 kPa/s
Release Rate	68947.6 kPa/s
Wheel Min. Spin Accel.	-3700 deg/s ²
Wheel Max. Spin Accel.	1000 deg/s ²
Tire Slip Max	0.15

DISCUSSION OF RESULTS

In simulations in PC-Crash of the movement of a vehicle braked on a μ -split, for default characteristics of both linear and TMeasy models, it can be noticed that the car stops outside the slippery surface ([Figures 14a and 16a](#)). Also, there were significant differences between the curves of accelerations and yaw velocities and the curves obtained in experiments ([Figures 15 and 17](#)). However, modification of tire parameters, and introduction of SL control even more so, guaranteed good compatibility.

In analogous simulations in HVE, for the adopted assumptions, good compatibility was reached of final positions and braking dynamic parameters. In case of TS model it was sufficient to keep default values of the braking system model parameters, while for the HVE Bosch model modification was necessary, described in the 'Simulations in HVE' section.

In the simulations of braking during a **lane change maneuver** by means of the two programs, the vehicle was contained within the given corridor or moved slightly outside. Since, however, the real car rode exactly on the border of the corridor (Figure 26), the results of all the simulations can be regarded as satisfactory. In case of the HVE Bosch algorithm the default values of *Wheel Spin Acceleration Min.* and *Max.* caused wheel locking. It should be remembered that the results shown in the diagrams refer to modified values.

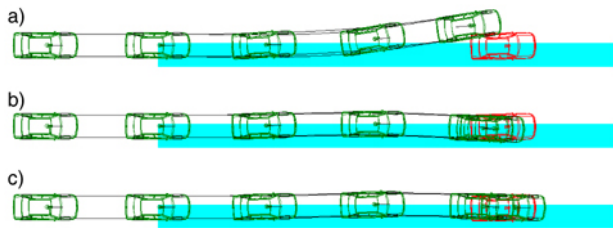


Figure 14. Simulated movement trajectory of a vehicle braked on μ -split with correction of steering wheel angle, for integration step 0.01 ms and linear tire model of characteristics: a) default, b) modified, c) modified with SL

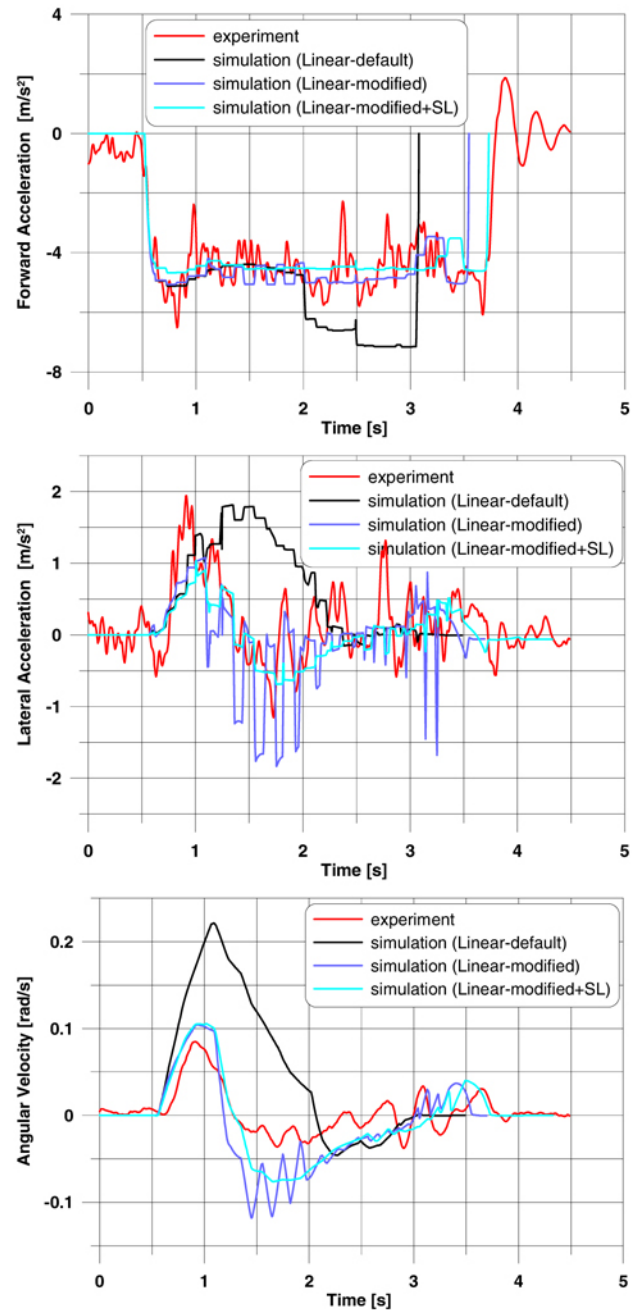


Figure 15. Time histories of accelerations and yaw velocities in experiments shown in Figure 14