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HARDWARE-IN-THE-LOOP TESTING OF VEHICLE'S ELECTRONIC STABILITY CONTROL SYSTEM

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Abstract:
Conducting laboratory and field testing is a classic approach to the development and certification of vehicles and their automotive components. These processes are costly and time-consuming. The serial installation of mechatronic systems in the car forced software and electronic systems engineers to master a new approach to testing and development - "physical" simulation (Hardware-in-the-loop). The aim of the research in this article is to develop, implement and validate a "physical" simulation method for evaluating the performance of Electronic Stability Control (ESC) systems. In this research, an ESC HIL-testbench, a mathematical model of the vehicle curvilinear movement in Adams Car, and a method for converting it into a Simulink-model, that allows generating a C-code, were developed and implemented. To assess the adequacy and correctness of the "physical" simulation, full-scale dynamic manoeuvres were carried out on the object of research - the Gazelle Next vehicle with ESC-system "Bosch ESP 9.1". In this article, the results of road tests and simulations, as well as an assessment of their convergence, are presented in tabular and graphical forms. The maximum discrepancy was 19% with the maximum allowable one up to 25% in accordance with the standard ISO 19635.

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1. INTRODUCTION

A vehicle is now more than just a "human-machine" system. Under the pressure of strict environmental regulations, and active and passive safety standards, challenged by global competition, OEMs (Original Equipment Manufacturers) are taking their products to the next level by integrating advanced driver assistance systems. Thus, a traditional "human-machine" interface is supplemented with a new element – an electronic control unit designed to assist the driver in critical situations, which is basically the first step to vehicular automation [1].

Throughout the entire period of the automotive industry development, one of the urgent tasks was to increase the active safety of vehicles: braking properties, as well as stability and controllability. The active serial application of semiconductors and computer technology created prerequisites for developing "smart" active safety systems. Electronic assistance systems were used for the first time in the 1970s with the adoption of the anti-lock braking system (ABS) [2]. With the development of state-of-the-art components, production technologies, and complication of mathematical algorithms, the system was gradually completed with new functions, such as anti-skidding, anti-rollover, traction control, and hill assist, together generally referred to as Electronic Stability Control System (ESC) [3, 4].

As these systems directly affect vehicle safety, they must comply with the strictest testing requirements [2]. OEMs have to find a way how to

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evaluate the efficiency of the new function with minimum time, cost, and effort. Obviously, traditional road tests are time-consuming and require substantial investments; moreover, there is always the risk of wasting a physical prototype, and making a critical error in the early design cycle [1]. A suitable solution was discovered in the aviation industry, where developers successfully applied real-time simulation for debugging and calibration while disregarding physical tests as impractical and expensive [5, 6]. It should be mentioned that the behaviour of some technical objects is difficult to describe with mathematical models, which means that numerical calculations need to be refined [7, 8]. The efficiency of such objects can be estimated via Hardware-in-the-Loop (HIL) simulation [9], where the object under control is replaced by a digital mathematical model synchronized with the ECU via the closed-loop systems [1, 10-12]. In other words, HIL simulates the driver's actions, driving parameters, and environmental conditions, and transforms them into digital and analogue signals, thus "convincing" the control unit that it operates on a real vehicle.

The key advantages of this technology are as follows: compliance with high requirements to vehicle testing, repeatability, simulation of a wide range of conditions, situations and design options for the evaluation of the algorithm efficiency, safety-related system tests with no risks for the driver [1, 13].

Also, it is worth noting that the main way to confirm the efficiency of electronic stability control systems for certifying vehicles is to perform dynamic manoeuvres on a real car in accordance with Appendix 21 of UNECE Regulations No. 13-11 [14] and No. 140 [15]. In its turn, these regulatory documents provide for the possibility of checking compliance with the regulatory requirements of vehicle modifications created on the basis of the base vehicle, taking into consideration the results of simulation on the HIL-test bench (Appendix 1 "Dynamic stability simulation" and Appendix 2 "Dynamic stability simulation tool and its certification"). Thus, the automaker has the opportunity to reduce time, money and human costs through using this technology for testing vehicles, equipped with ESC systems.

Considering the high relevance of this field of study, the task was given to develop a hardware-software platform for the HIL tests of Bosch ESP 9.1 (ESP stands for Electronic Stability Program, which is the brand of ESC system, 9.1 - version of the product) systems installed in GAZelle Next light commercial vehicles with maximum total weight 3.5 tonnes (LCV class). This paper is specifically devoted to the above-mentioned functions, as they are mandatory for all new vehicles developed in Russia (as in many other countries of the world) according to the current legislation.

The task was completed in several stages: first – to develop a hardware part which includes components of a real brake system, and its electrohydraulic ECU; second – to develop a mathematical model emulating the driving behaviour of the vehicle; third – to link the hardware and the software parts together via the synchronization device ("real-time PC"); fourth – to perform physical tests, validate and verify the hardware-software platform. A detailed description of each stage is provided below.

2. MATERIALS AND METHODS

2.1 Hardware-software platform components

Following previous studies by scientists [4, 9, 13, 16-19], it was gathered and implemented ready-to-use hardware and software components to a HIL - test bench, so it consists of three main elements (Fig. 1).

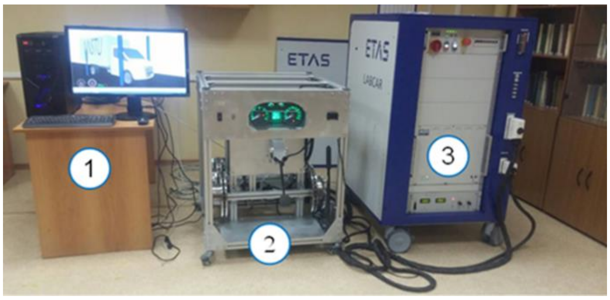
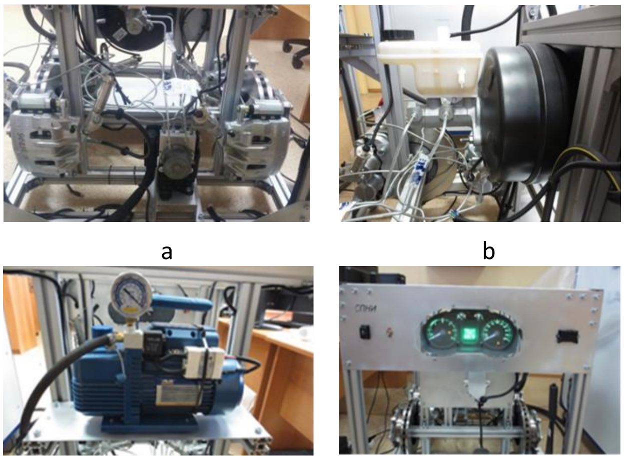


Fig. 1. Hardware and software platform of ESP HIL-test bench. 1 – software part; 2 – hardware part; 3 – RTPC

The hardware part (Fig. 1, Pos. 2) is an aluminium frame with the tested vehicle's brake system components installed on it, as well as auxiliary pressure measuring sensors embedded in the hydraulic drive. The software part (Fig. 1, Pos. 1), includes a PC used to develop and adjust the vehicle driving model for the tests. The real-time PC (Fig. 1, Pos. 3), which synchronizes the hardware part and the virtual model via the interface (CAN-bus, RS232, 485, Ethernet), data buses or digital and analogue I/O boards, and performs calculations in real-time [9, 11, 12, 18, 19].

Hardware components are presented in Fig. 2. Brake system components (brake pedal, master and servo cylinders, ESC control unit) are mounted on the aluminium frame and connected via standard hydraulic hoses (Fig. 2a, b). A non-standard vacuum pump (Fig. 2c) exhausts the air, thus enabling the operation of the brake booster. ESC system generates excessive pressure of the brake fluid in the servo cylinders, which establish a connection with the model via BD Sensors DMP331 0-25 MPa hydraulic sensors (Fig. 2a), with the outcoming signals processed by the input board of the interface device. To visualize the experiment (i.e. to control speedometer and tachometer readings, warning lights actuation), the front part of the test bench is equipped with an instrument cluster, an OBD-II socket to connect a diagnostic tool if necessary (a reading of DTC – Diagnostic Trouble Codes, a conducting calibration tests of acceleration sensors, an activating the air removal mode from the hydraulic drive, a checking the integrity of the valve coils), buttons for simulation of engaged reverse gear and the ESC forced shutdown (Fig. 2d).



a b

c d

Fig. 2. Hardware part of the NNSTU HIL. a – ESC electrohydraulic unit and servo brake mechanisms; b – master cylinder with a vacuum booster; c – vacuum pump; d – front view, dashboard

The RTPC-part is represented by LABCAR high-speed real-time processor by Etas GmbH (Fig. 1, Pos. 3), which executes mathematical models generated in Simulink or ASCET, with a fixed iteration step of 0.001 seconds. This real-time PC includes the following components: Delta SM52-AR60 power source to supply the current (up to 50 amperes) to the ESP electro-hydraulic unit; ES5300 RTPC central unit (Intel core i7, 2 x 4096 MB DDR3, 500 GB SATA) to execute the mathematical model; ES5321.1 digital/PWM I/O board to emulate and read the data from the buttons, switches, as well as the control of the power relay of the stand; ES5350.1 analogue I/O board to process the readings from the pressure sensors; PB5338CURR.1-A board to simulate current wheel speed sensors; CAN-IB600/PCIe board (2-channel) to transfer data between the model and vehicle control units (ESC, engine ECU, and instrument cluster); Ethernet-interface to connect the software part with the real-time PC.

A mathematical model is developed and optimized (HIL software part) on a Windows 8 PC (core i7, 4 x 4096 MB DDR3, 1 TB SATA) with the following software: LABCAR-OPERATOR (tuning and controlling the real-time processor), MSC Adams Car and VI-grade (developing a mathematical model emulating driving behaviour of the vehicle), MATLAB/Simulink (generating a C-code from a vehicle motion model). Model development stages are described below.

2.2 Virtual model of the vehicle

Developing a mathematical model for driving behaviour simulation requires time and resources. First, based on the task (linear or curvilinear motion simulation) and possible assumptions, a system of differential equations is generated and integrated into the simulation environment. Then parameter values are defined by experiment and according to the data from design documents. Finally, the model is verified and validated. Thus, developing a highly reliable mathematical model takes over a year [8, 20, 21].

Eq. and the graphical scheme (Fig. 3), which generally describe the curvilinear motion of the GAZelle Next vehicle, are presented below.

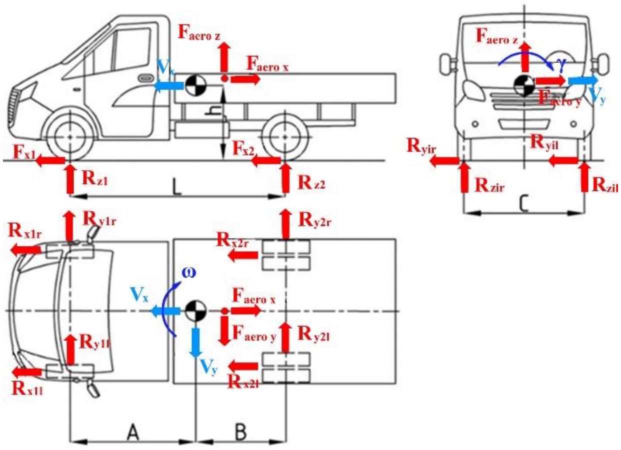


Fig. 3. Calculation scheme of vehicle dynamics

$$V_x' = \frac{1}{m}\left(R_{x\cos\alpha} - R_{y\cos\alpha} - R_{z\cos\alpha}\right) + V_y\omega \quad (1)$$

$$V_y' = \frac{1}{m}\left(R_{y\cos\alpha} - R_{x\cos\alpha} - R_{z\cos\alpha}\right) - V_x\omega \quad (2)$$

$$\omega'' = \frac{1}{J_z}\frac{B}{2}R_{\cos\alpha} +$$
$$+\frac{1}{J_z}\frac{B}{2}\{L(R_{-x\sin\alpha} - fR_{z\sin\alpha} + R_{+y\cos\alpha}) - M_{res}\} \quad (3)$$

$$\gamma'' = \frac{1}{J_x}\left\{h(R_{x\sin\alpha} + R_{y\sin\alpha} - fR_{z\cos\alpha}) - \frac{B}{2}R_{-z}\right\} \quad (4)$$

Where:

$$R_{x\cos\alpha} = \sum_{i=1}^{n}(R_{xir}\cos\alpha_{ir} - R_{xil}\cos\alpha_{il}) \quad (5)$$

$$R_{y\cos\alpha} = \sum_{i=1}^{n}(R_{yir}\cos\alpha_{ir} - R_{yil}\cos\alpha_{il}) \quad (6)$$

$$R_{z\cos\alpha} = f\sum_{i=2}^{n}(R_{zir}\cos\alpha_{ir} - R_{zil}\cos\alpha_{il}) \quad (7)$$

$$R_{\cos\alpha} = \sum_{i=1}^{n}\{\cos\alpha_{ir}(R_{xir} + R_{yir} - fR_{zir})\} -$$
$$-\sum_{i=1}^{n}\{\cos\alpha_{il}(R_{xil} + R_{yil} + fR_{zil})\} \quad (8)$$

$$R_{-x\sin\alpha} = \sum_{i=1}^{n}(R_{xir}\sin\alpha_{ir} - R_{xil}\sin\alpha_{il}) \quad (9)$$

$$R_{z\sin\alpha} = \sum_{i=1}^{n}(R_{zir}\sin\alpha_{ir} + R_{zil}\sin\alpha_{il}) \quad (10)$$

$$R_{+y\cos\alpha} = \sum_{i=1}^{n}(R_{yir}\cos\alpha_{ir} + R_{yil}\cos\alpha_{il}) \quad (11)$$

$$M_{res} = \sum_{i=1}^{n}(M_{resir} + M_{resil}) \quad (12)$$

$$R_{x\sin\alpha} = \sum_{i=1}^{n}(R_{xir}\sin\alpha_{ir} + R_{xil}\sin\alpha_{il}) \quad (13)$$

$$R_{y\sin\alpha} = \sum_{i=1}^{n}(R_{yir}\sin\alpha_{ir} + R_{yil}\sin\alpha_{il}) \quad (14)$$

$$R_{z\cos\alpha} = \sum_{i=1}^{n}(R_{zir}\cos\alpha_{ir} + R_{zil}\cos\alpha_{il}) \quad (15)$$

$$R_{-z} = \sum_{i=1}^{n}(R_{zir} - R_{zil}) \quad (16)$$

where V_x', V_y' are linear accelerations about the respective axes (m/s^2); m is vehicle mass (kg); R_{xi}, R_{yi}, R_{zi} are longitudinal, transverse, and vertical reactions, respectively in the contact patch of i-th wheels, index l is left bort, r is right (N); α_{ir} and α_{il} are angles of rotation of the steered right and left i-th wheels, respectively (deg); f is rolling resistance coefficient; V_x, V_y are vehicle speeds relative to the longitudinal and transverse axes (m/s); γ, ω are angles of rotation relative to the longitudinal and vertical axes (deg); γ'', ω'' are rotational accelerations about the longitudinal and vertical axes (^{0}/s); J_z is the moment of inertia of the vehicle about the vertical axis (kg·m^2); h is the height of the center of mass (m); B is the distance from the rear axle to the centre of mass (m); L is the vehicle base (m); M_{res} is the moment of resistance to turning wheels (N·m); M_{resir}, M_{resil} are the moment of resistance to turning i-th wheels of the right and left bort.

The solution of this system of differential equations by numerical methods can be implemented in various software packages. For example, in the MATLAB/Simulink graphical programming environment, allows you to get a graphical representation of the change in the dynamic parameters of the object under various conditions at the output. The disadvantage of this approach is the high initial complexity associated with the correct writing of the solution to the system of differential equations and the implementation of the initial and boundary conditions.

Considering all the difficulties of developing a model from scratch, in practice engineers and scientists use software packages that already have a “constructor” of a virtual model and the modeling process is debugged by the developer. Thus, the Adams Car model, previously tested in the MSC environment, was used.

During real-time testing of electronic control units, the synchronizing device (LABCAR) can operate only with the C-code generated from an earlier model [22]. The code generation is currently supported by various software tools, including MATLAB/Simulink, ASCET, Labview and others. However, Adams Car is not on the list, so conversion options were searched.

With support from MSC Software, VI-Grade, and Mathworks, the following algorithm for conversion of a multibody system (MBS) was obtained (Fig. 4). MBS model of a GAZelle Next takes into account all the necessary parameters of the tested object: mass-inertia characteristics, the rigidity of elastic elements, suspension and steering kinematics, etc.

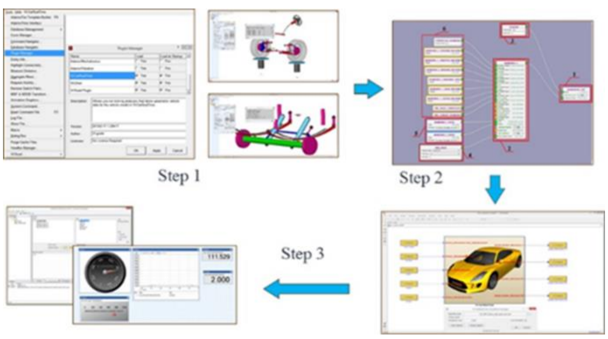


Fig. 4. MBS-model conversion to C-code

Step 1 - to convert the model from MSC Adams Car to VI-Grade, which has a special plug-in enabling transfer from a multi-body system to a five-body model (sprung weight and four wheels) described by polynomial equations. Step 2 - to define environmental impact (road surface, atmospheric conditions), initial driving conditions, and a driver's behaviour (control of the engine, clutch, gearbox, steering wheel). Step 3 - Export the model to MATLAB/Simulink and generate the C-code. Vi-Grade developers compiled a library for Simulink conversion. Virtual I/O ports are connected to the real ports via Etas Experiment Environment software, enabling C-code generation and simulation launch.

This approach allows engineers to perform "physical" simulations, which used to be exclusively available only for software programmers and specialists with a deep knowledge of physics and mathematics.

2.3 Initial data for modelling

The accuracy and reliability of the input data play an important role in modelling.

Part of the characteristics (gear ratios, geometry) laid down at the production stage can be obtained from the design documentation, but most are private. In this regard, significant work was carried out:

a) Aerodynamics. Since most of the planned manoeuvres are carried out at speeds above 40 km/h, the aerodynamic force F_w has a significant effect on the deceleration of the vehicle (from theory, F_w is known to be directly proportional to the square of the speed).

The midsection A_{mid} was calculated in the software using a virtual model of the vehicle body.

The aerodynamic drag coefficient C_x was determined experimentally by the "free run" method: at the test site, the vehicle accelerates to 100 km/h, the neutral mode is switched on, and the motion is carried out to a complete stop. During the experiment, the speed and time of the motion are recorded. Racelogic Vbox 3i 100Hz, which calculates the speed based on the GNSS technology (GPS, Glonass), was used. It should be noted that this measuring equipment uses an inertial system (gyroscope), which is necessary for calculating the Kalman filter, thus ensuring high accuracy of the data measurement, the error of which occurs due to phase inhomogeneity of the atmosphere and satellite changes.

The Eq. for determination of the calculated C_x [23]:

$$C_x = \frac{2m(a_{Vh}-a_{Vl})}{A_{mid}\rho(V_{High}^2-V_{Low}^2)} \tag{17}$$

$$a_V = \frac{V_i-V_{i+1}}{0.01} \tag{18}$$

Where a_{Vh}, a_{Vl} - deceleration at high and low speeds (m/s^2), A_{mid} – midsection (m^2), m - car mass (kg), ρ - air density (kg/m^3), V_i and V_{i+1} - speeds at the i-th and i + 1-th intervals of movement (m/s).

The data were recorded at 100 Hz; therefore, in Eq. (18) writing frequency was 100 Hz. a_{Vl} is subtracted from a_{Vh}, thus considering the influence of road resistance forces and transmission losses.

The graph of speed measurement versus time is shown in Fig. 5.

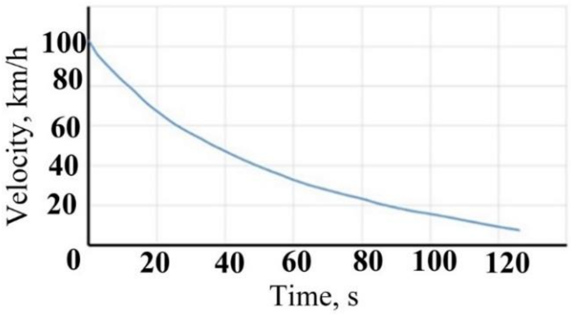


Fig. 5. Variation of speed with time in the "free run" test

b) Moments of inertia. The moments of inertia of individual rotating elements were determined using a trifilar suspension, and to calculate the inertia of the car, a stand platform was developed and manufactured, the schematic diagram of which is shown in Fig. 6.

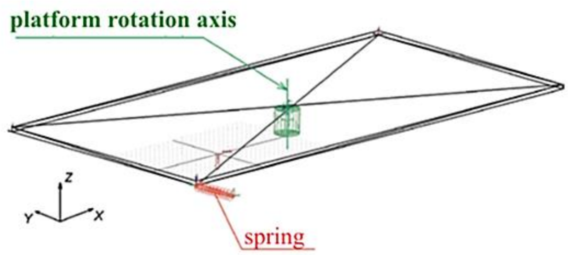


Fig. 6. Platform configuration for measuring the moment of inertia of the vehicle about the vertical axis

The moment of inertia is calculated by the following equation. [24]:

$$J = \frac{(T_a^2-T_p^2)cl^2}{4\pi^2} - md^2 \tag{19}$$

where m – is the mass of the vehicle (kg); c - the stiffness of the spring; d – is the distance between the centre of mass of the car and the axis of rotation (m); T_a - the oscillation period of the platform without a car (sec); T_p - the oscillation period of the platform with the car (sec); l - the distance from the spring attachment point to the axis of rotation (m).

c) Characteristics of the interaction of the standard tire with the roadway.

Research work with the Cordiant Business CA-1 185/75 tire was conducted in France with help from Dufournier Company. As a result of the experiment, an array of data was obtained; having processed it in MSC Adams tire tools, a PAC2002 file was configured that describes the characteristics of a car tire. As you know, PAC2002 uses an approximating trigonometric polynomial, developed by the Dutch scientist Pacejka, and contains its coefficients.

Longitudinal and transverse friction coefficient (Y) is calculated by the following Eq., which is called the "magic formula" [25]:

$$Y = D\, sin\{C_p\, arctan[B_p x - E(B_p x - arctan\, B_p\, x)]\} \quad (19)$$

where Y can be the longitudinal and transverse friction coefficient, respectively, D, C_p, B_p, and E are some constants obtained experimentally, and x is the slip parameter depending on various conditions.

The car tire was tested in 3 loaded states, namely the vertical force was 4000, 6000, and 8000 N, as the most characterizing tire's operating modes of the vehicle Gazelle Next. Coefficients D, C_p, B_p, and E, obtained from the results of processing field tests [26], are presented in Table 1.

Table 1. Pacejka's experimental coefficients

Load (N)	D	C_p	B_p	E
4000	0.85	1.5	0.00006	1
6000	0.8	1	0.0003	4
8000	0.8	1	0.0002	6

2.4 Preparation and carrying out of field tests

Arguably, the most important stage of development is to check the model against the real-world test results. Accordingly, several road tests were performed to compare the results with the simulation

The object under test was GAZelle Next LCV with base 3145 mm, equipped with Bosch ESP 9.1 electronic stability control system. This vehicle was curb weight with an additional load 100 kg (operator + steering wheel robot).

As per UNECE Regulations No.13 [14], the following dynamic manoeuvres have to be performed to confirm ESC efficiency: turning with a radius of 35 meters (GOST 31507-2012) [27]; lane change 20 meters (GOST 31507-2012); double lane change (ISO 3888-2 [28] and ISO 3888-1 [29]); sine with dwell (Global Technical Regulations No. 8 [30]); "fish hook" (NHTSA) [31]; asymmetric sine; step steer (GOST 31507-2012); lane change (20 meters) with a switch from a high to low friction coefficient.

For verification, a wide range of dynamic parameters and functions has to be compared. In this research, the following critical parameters were selected: linear speed (km/h); longitudinal and lateral acceleration (m/s^2); pitch, roll, and yaw rate (^{0}/s); path; wheel breakaway moment; excessive pressure in servo cylinders (MPa); driver's actions (steering angle, accelerator/brake/clutch pedal engagement); response time for ESC functions (ABS, EBS, ROM, RMI, VDC, TCS); impact ESC to engine torque; engine's parameters (revolutions per minute, torque); wheel's speed (km/h).

To record the parameters in real-time during the manoeuvres, the following measuring and additional equipment were installed in the vehicle: Racelogic Vbox 3i 100Hz (Fig. 7d) with IMU04 gyroscope uses GPS/Glonass to measure dynamic parameters of the vehicle and travelling path, records data from the on-board CAN-bus, and acquires data from additional sensors; DGPS telemetric station defines exact geolocation n Real-Time-Kinematics mode; DMP331 pressure sensors in servo cylinders (Fig. 7e, f); Riftek laser sensors are mounted on the vehicle body to record the wheel breakaway moment (Fig. 7c); Steering robot OrbitTD from AB Dynamics can be used in the tests where it is necessary to make a precise measurement of the impact on the steering wheel (Fig. 7b); previously developed anti-roll device (outrigger) ensures safety during dangerous manoeuvres (Fig. 5a).

The design of the outrigger was developed based on results of the NHTSA research (National Highway Traffic Safety Administration - USA) and other experiments. The anti-rollover device considers the design features of Gorky Automobile Plant light commercial vehicles. It withstands the required load, which was confirmed by strength calculations and full-scale tests, as a result of which a certificate of conformity was obtained [32].

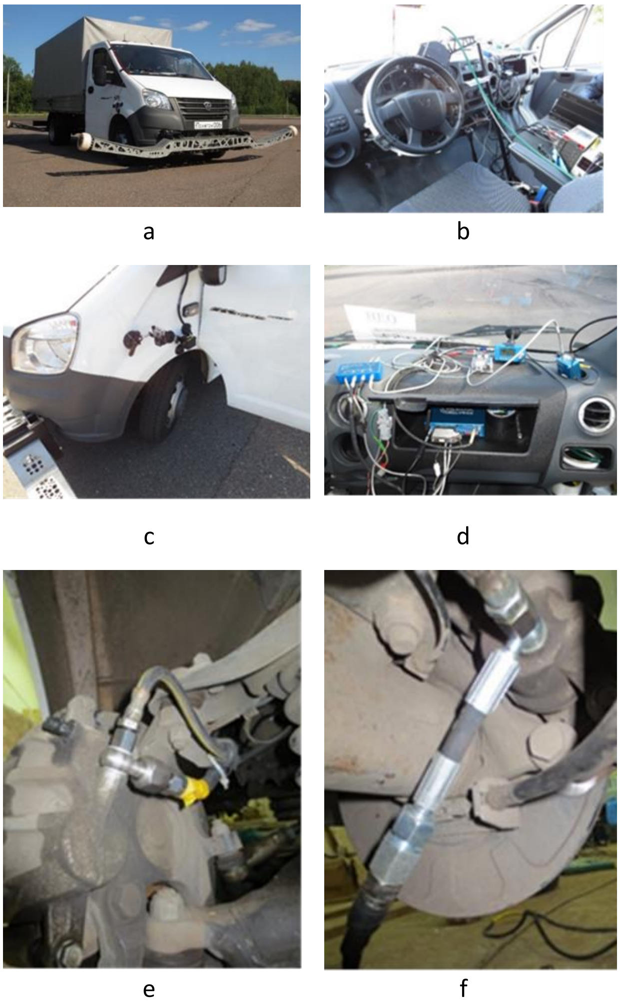


Fig. 7. Measuring and additional equipment. a – vehicle with outriggers; b – "steering" robot; c – wheel breakaway sensor; d – Racelogic Vbox 3i; e – front servo cylinder pressure sensor; f – rear brake mechanism pressure sensor

3. RESULTS AND DISCUSSIONS

To assess the convergence of the experiment and simulation in this research it was used the generally accepted international standard ISO 19365 [33]. It uses manoeuvre "sine with dwell". Test methodology is described in UNECE Regulations No. 13-11 [14] and Global Technical Regulations No. 8 [30]: a vehicle will accelerated up to 80 km/h, then a driver will release the accelerator pedal and activate a "steering" robot, which will high-speed turn a steering wheel in a pre-determined manoeuvre (Line 1 in Fig. 8).

Validation results of real tests and modelling are presented in Table 2 and Fig. 8.

In addition, graphs of comparison of simulation and experiment for movement speed and longitudinal deceleration are presented in Fig. 9 and Fig. 10, respectively.

Table 2. Validation results

Para-meter	Received values		Received discrepancy	Maximum discrepancy as per ISO 19365
	Road test	Simulation		
1 peak of the yaw rate (^{0}/s)	-23.5	-22.47	4.1 %	±15 %
2 peak of the yaw rate (^{0}/s)	24.44	29.15	19 %	±25 %
Zero transition period for the yaw rate (s)	1.15	1.19	0.04	±0.1 s
Lateral displace ment of the centre of gravity (m)	4.64	4.22	7.5 %	±18 %

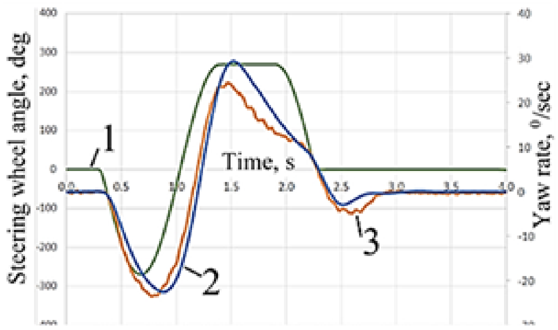


Fig. 8. Correlation between simulation and road test. 1 – Impact on the steering wheel; 2 – yaw rate in the road test, 3 – yaw rate in the simulation

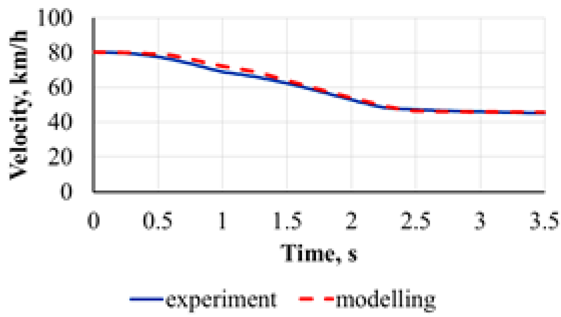


Fig. 9. Comparison of vehicle speed

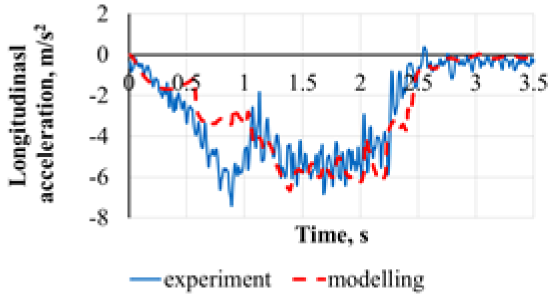


Fig. 10. Comparison of vehicle deceleration

Hardware-In-the-Loop testing of an automobile's prototype or its automotive components is a very perspective trend because it allows reduce production costs and avoids critical development mistakes. This is especially true for active safety systems such as ABS/ESC. Currently, many Russian and foreign scientists are engaging in this topic. After analysing scientific works of authors: Dygalo Vladislav "VSTU", Ryazantsev Valentin "FSUE NAMI", Taehun Hwang "Kookmin University", Herbert Schuette "dSpace GmbH", Ayman A. Aly "Assiut University", Massimo Violante "Politecnico di Torino" - it was developed and produced ESC HIL-testbench consisting 3 parts: RTPC-machine LABCAR; hardware and software parts.

For verification of the model road tests were carried out. According to the results presented in Table 2, sufficient convergence of the simulation and the experiment was obtained. The maximum discrepancy is 19% in the parameter "second peak of the yaw rate" at the maximum allowable one up to 25% according to the international standard ISO 19365 [33]. Discrepancies of other control parameters are less than 8%. It is also worth noting, that the nature of curves change of experiment and simulation are identical (Line 2 and 3 in Fig. 8), which confirms the correctness of the vehicle's physics motion modelling.

It is necessary to note the limitations of the study. The experiment was carried out only in one loaded state (curb weight + 100 kg). Now there is a plan to conduct long-term volumetric tests in other load states (half and full), with different bases (3145, 3745, 3950 mm) and a variable height of the centre of gravity - which ultimately will allow for a full validation and verification of the HIL-test bench. Complex studies are required for stand certification according to the standard UNECE Regulations No. 13-11 [14].

4. CONCLUSION

The hardware-in-the-loop test bench to perform an evaluation of the ESC system, installed in GAZelle Next light commercial vehicle, was developed and implemented successfully.

An engineering method for converting the MSC Adams Car multi-body mathematical model to C-code was developed to speed up preparation for real-time testing and reduce technical personnel's IT training.

The similarity between the real test results and the simulation is very high. Therefore, in the future this test bench can be used for calibration, fine-tuning works and pre-certification testing according to UNECE Regulations No. 13-11 [14] vehicles, equipped with the ESC electrohydraulic unit. After carrying out complex tests there is a prospect of approving the usage of the HIL-stand in certification tests of vehicle modification (for example: lengthening the frame, re-equipment for medical, fire-fighters, and concrete).

In conclusion, it is worth noting, that the main way to confirm the efficiency of electronic stability control systems for certifying vehicles is to perform dynamic manoeuvres on a real car in accordance with Appendix 21 of UNECE Regulations No. 13-11 and No. 14. Thus HIL-testing – is only an additional alternative way for certifying the modification of vehicles with ESC.

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