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IDENTIFICATION OF PACEJKA MODEL PARAMETERS OF A LIGHT COMMERCIAL VEHICLE TIRE FOR DYNAMIC RESEARCH

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This article is devoted to the research of the interaction of the wheel of a GAZ light commercial vehicle with a hard supporting surface. The relevance of this problem is due to the need to adequately reproduce the force reactions acting on the tire in the contact patch, when modelling the vehicle dynamics. High similarity of the real process and its modelling are guaranteed if there is a significant empirical data set for a particular tire model, which can be ensured only by the results of field tests. Specialists from Nizhniy Novgorod State Technical University have developed a schematic diagram of a road measuring unit, a test methodology and built testing unit as well as conducted full-scale tests. The experiment was conducted in the auto racing track at an ambient air temperature of 20 °C on a dry road asphalt surface with a high friction coefficient (0.4 – 0.8). The resulting array of experimental data was processed and presented in numerical trigonometric polynomials form (PAC 2002). The table comparing theoretical and experimental values presented in the results of this article confirms the high level of convergence. The maximum discrepancy in absolute value does not exceed 5%.

Keywords: slip ratio, field testing, braking, modelling, "magic" formula

1 INTRODUCTION

The invention of the first pneumatic tire dates back to 1845. Since these 150 years the automobile tire has undergone significant changes from the materials used in its manufacture (natural and synthetic rubber, metal and viscose/capron threads, etc.) to its construction [1, 2]. However, despite all the trends and technological advances, the understanding that in the driver-car-road system interaction of the wheel with the roadbed plays one of the most critical roles remains unchanged. In this regard, the study of this issue since the early 1950s has received considerable attention from both foreign scientists and Russian experts. It is worth highlighting the works of the following scientists: Pacejka [3], Chudakov [4], Knoroz [1], Raklyar [5], Bromberg, Neimar, Fufaev, and Khachaturov [6, 7].

It is worth noting that in modern automotive engineering, a surge of interest in the theory of pneumatic tire operation was caused by the active introduction of electronic systems responsible for the active vehicle safety: anti-lock braking (ABS), traction control system (TCS), electronic stability control (ESC) with an operating algorithm based on the assessment and prediction of kinematic parameters of interaction between the wheel and the road surface [8-10].

The relationship between the kinematic parameters of the wheel and the realization of the pushing or braking forces was studied as early as the second half of the 20th century and is graphically presented in Fig. 1 [11–13]. As can be seen from the diagram, the maximum stable longitudinal and transverse stability is provided in a small area of wheel slip (Scr) [14]. The operation of the car anti-blocking system is based on maintaining this mode of wheel rolling [10, 15].

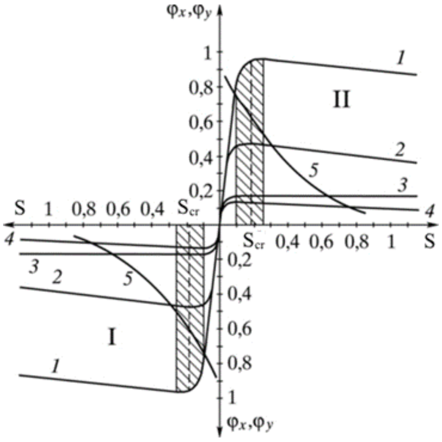


Fig. 1. Diagrams of the relationship between the traction coefficient and wheel slip. I, II – traction and braking modes, respectively, 1 – dry asphalt, 2 – wet concrete, 3 – wet paving stone, 4 – rolled snow, 5 – cross direction for dry asphalt.

It should be noted, that Fig. 1 shows the basic view of the diagram φ(S); the qualitative view differs from one tire to another. This is due to a wide variety of the market manufacturers, materials used, and tread patterns.

When calibrating the ABS, TCS, and ESC systems, there is no need to determine these functional relationships [16]. The efficacy of the system is adjusted by polygon tests, i.e., by selecting response coefficients experimentally, but this does not underestimate the importance of such studies. The trend in modern automotive engineering is to accelerate the development of the vehicle and its systems using simulation technology. This can be the assessment of traction speed, braking, fuel-economic properties, controllability stability, and hardware-in-the-loop simulation of the algorithm of electronic systems [10, 17]. Thus, obtaining real data on the interaction of the wheel with the supporting surface is one of the most important tasks in virtual testing of the vehicle [18].

This article will present the result of the long-term work of scientists and specialists of Russian State Technical University, which was tasked to obtain experimental data on the interaction of the wheel with the road surface (dry asphalt) of the light commercial vehicle GAZelle. Next. The purpose of this research is to obtain a verified Pacejka model for use in modeling the curvilinear movement of a vehicle.

2 MATERIALS AND METHODS

Over 70 years of research into the physics of the friction-rolling process of a wheel on a bearing surface, 2 experimental approaches have been identified in obtaining such empirical characteristics:

- Bench
- Road

Each of these methods has its pros and cons. The first is the development and implementation of a platform tire bench (Fig. 2a). It provides high-quality separation and control of influencing factors, which has a positive effect on the accuracy and stability of the results obtained, but it usually uses a steel belt or drum as a roadbed [6, 19], so one cannot ensure high similarity of the experiment with real operating conditions. Stationary test benches are usually used by automobile tire manufacturers in direct research, design, and inspection work [20-22]. When engineers face the task of stochastic modeling the complex object behavior (a car) in real operating conditions, they resort to road tests with the use of trolley benches (Fig. 2b). At the output, one gets data on the wheel interaction with the specific road on which the tests were conducted [23, 24].

a

b

Fig. 2. Tire test benches. a – stationary [17], b – road [19]

As noted above, our specialists were tasked to measure and then analyze the experimental data of the wheel interaction of the light commercial vehicle GAZelle Next. This problem was solved as part of the development, implementation, verification, and validation of the bench of hardware-in-the-loop simulation of the vehicle dynamics equipped with an electro-hydraulic braking system with ABS/ESC functions. Taking into account the pros and cons of each approach, it was decided to focus on road testing, so when simulating the braking properties, it is planned to provide maximum convergence with the testing range of electronic systems [25].

2.1 Tire bench

A huge number of studies (since the mid-1970s) by both Russian and foreign experts are devoted to the development of road tire stands [1, 23, 24].

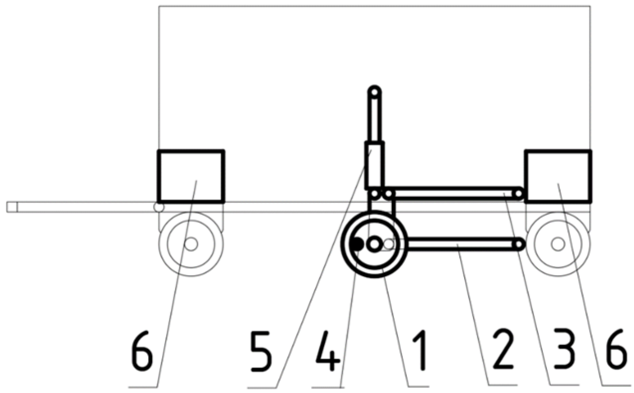
In general terms, they can be divided into two classes [26]:

- Based on a production car [27–29]
- Based on a trailer [5, 17, 24]

An unambiguous advantage of the first method is the simplicity of creating a measuring installation, that is, a set of measuring equipment are installed on the car (navigation system, sensors of wheel speeds, and pressures in the brake drive). The challenge in this method is the determination of changes in the force parameters acting on the wheel, which is possible only with the help of an expensive strain-measuring hub or an indirect method of recalculating the mass distribution [25, 26]. It is also worth noting that when testing in this case, it is challenging to maintain the repeatability of measurements, which in turn affects the final result.

The second method is preferable, but because of the significant preparatory stage (development, design, manufacturing, and debugging of the test bench) is more labor-intensive. However, the final result of the study covers the entire range of operating and performance characteristics of the tire. It should be noted that similar tire benches developed by Soviet and Russian scientists [1, 5, 9] could measure only longitudinal characteristics of a car wheel, but in terms of drivability and stability, researchers are interested in the relationship between longitudinal slip and lateral traction coefficient, so the bench design shall be implemented to measure transverse characteristics. The schematic diagram of these benches can be found in the works by foreign scientists [24, 26].

In Russian science, there is no accumulated experience in conducting such high-tech research. In this regard, it was decided to become familiar with the experience of foreign colleagues in this matter. It is worth noting that most of the world's centers for car testing and certification are equipped with tire trailers, but accordingly, the services of such measurements are costly [30]. One should mention the work of specialists from the following companies: Defunier (France), TASS International (Poland), Maxtrax (Australia), Idiada (Spain), and Tuv (Germany).



a

b

Fig. 3. Tire test bench used by NNSTU. a - Schematic diagram of a trail lab for the study of the dynamic characteristics of tires, b – Prototype of a trail lab. 1 – the studied tire; 2 – lower arm; 3 – upper arm; 4 – electrohydraulic drive of the slip angle; 5 – vertical force electrohydraulic drive on the wheel; 6 – ballast

The schematic diagram and prototype of the road test bench for tires used by our scientists are shown in Fig. 3. Technically, it is a cargo trailer with a modified supporting frame. The design changes were necessitated by the need to place the unit for dynamic tire rolling studies inside the trailer. The unit includes the following components (Fig. 3a): the studied tire (item 1); lower and upper arms (items 2 and 3, respectively); electro-hydraulic actuators for the slip angle (item 4), and vertical force on the wheel (item 5). The guide mechanism positions the wheel relative to the trailer. Loading and orientation of the examined tire are done through hydraulic cylinders and braking mechanisms controlled by automation. The force and kinematic parameters of the wheel are measured with a strain hub.

2.2 Conducting field tests

Cordiant 185/75R16 tires (3 pcs.) were selected as the object of the study, serially installed on a light commercial vehicle GAZ. The tire has the following design parameters: radial, tubeless design, tread pattern – special, weight - 12.2 kg, speed index - Q (160), load index - 104/102, outer diameter - 684±7 mm, sectional width - 185 mm, static radius - 318±3 mm, maximum tire load – 900/850 kg

The study consists of measuring forces and torques transmitted by the wheel hub as the tire rolls on the road in certain modes, which are characterized by vertical force, slip angle, transverse slip angle, and slip coefficient. The range of values for each parameter was chosen based on the design features of the tire, the manufacturer's recommendations, and the analysis of the tire operating modes on the studied vehicle.

Tests were conducted at an ambient temperature of +20 °C on dry asphalt pavement. A total of about 70 runs were made with all 3 tire samples. Main tests performed: rolling with slip, combined rolling with slip and braking, rolling with slip and different transverse inclination angles, combined rolling with slip and braking at different transverse inclination angles, determination of longitudinal stiffness (a blocked tire is rolled out of place), determination of the force accumulation path (the tire set at the slip angle with the maximum traction coefficient is pulled forward to see the length of the maximum lateral force accumulation path), determination of the force accumulation path with different transverse inclination angles.

Before testing, a preparatory stage was carried out, the purpose of which was to warm up the tire surface to the operational mode, which consisted in dragging about 1 km along a straight line in the rolling mode with a slip (-18°, +18°). The preparation warms up the tire from +10 °C to +40 °C. It is worth noting that during all studies, the maximum recorded temperature was about +80 °C. The average temperature during the study was about 50 °C.

The studies were carried out under the following loading modes: vertical load - 4000 N, 6000 N, 8000 N; slip angles - -18° +18°; transverse inclination angles - -5°, 0°, +5°; linear speed of tire testing– from 70 to 80 km/h.

The following data were recorded using the measuring equipment installed on the test bench: transverse inclination angle of the wheel, slip angle, rolling radius, longitudinal sliding coefficient, longitudinal force, transverse force, vertical force, stalling torque, self-aligning torque, longitudinal velocity, tread surface temperature, coating temperature, wheel speed

A strain hub was used to measure the force and kinematic characteristics acting on the wheel, a Racelogic Vbox GNSS device with a set of non-contact temperature sensors recorded the linear characteristics of the trailer movement, temperature parameters of working surfaces, and acted as a dynamic data acquisition system that processes and captures information from all installed measuring equipment.

At the end of the experiments, each tire was rolled again in the "rolling with slipping" mode to assess degradation.

As a result of these tests, an array of experimental data characterizing the interaction of the wheel with the bearing surface was obtained.

3 RESULTS

The processing of the measured data revealed the presence of values falling out of the general course of the physical process. Because of the large number of such numbers, it was not possible to select samples manually. For filtering purposes, a special algorithm was developed in the Visual Basic environment based on the moving average function, but with additional conditions ensuring the uniformity of the output data on the slip coefficient or slip angle.

Eventually, the filtered data was loaded into a special Tire Tools utility of the MSC Adams car software, the output of which was a specialized tire model file PAC2002 containing a semi-empirical description of light commercial vehicle tire performance modes in all acceleration/deceleration operating modes.

Let us present some part of the experimental data graphs (at different vertical loads and wheel slip angles), which are of the greatest interest in terms of steerability and stability under braking (Fig. 4, 5).

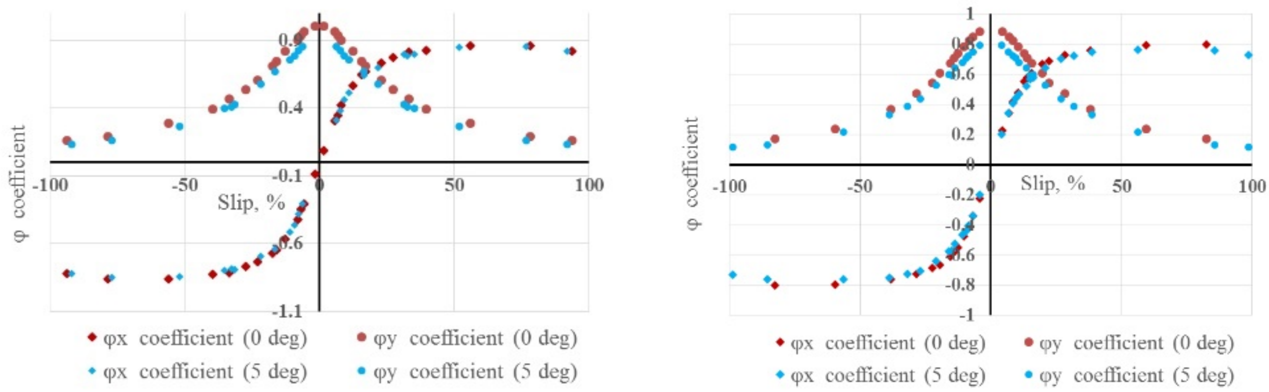
Indirect confirmation of the correctness of the obtained data is the physical sense of the operation of the ABS system of the car, which states that the steering and stability of the car tire are provided at a wheel slip of 10–40% [7, 8]. As can be seen from the graphs, when the longitudinal slip goes into the zone of more than 50%, the physics of wheel rolling becomes unstable, thus increasing the probability of lateral slip, which is dangerous for road traffic.

According to the works by the Dutch scientist Pacejka, the dependence of the adhesion coefficient on slip can be described by the following trigonometric polynomial called the "magic formula" [3, 7]:

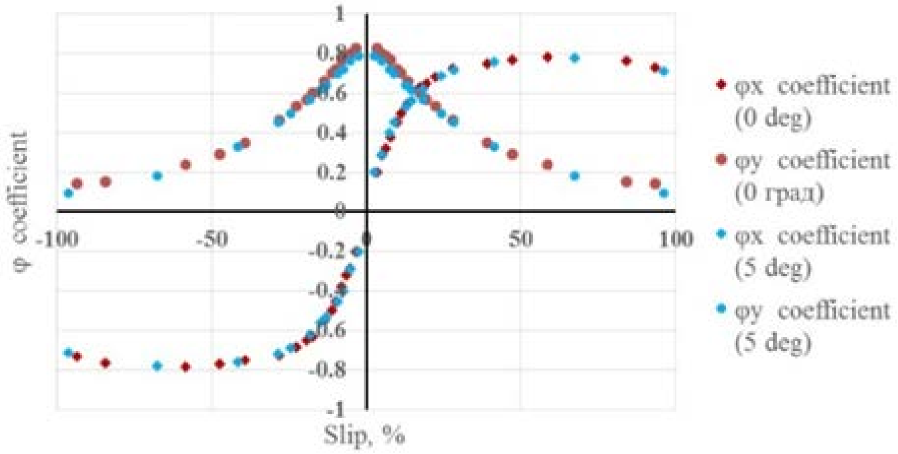
$$Y = D\sin\left\{C\arctan\left[Bx - E\left(Bx - \arctan Bx\right)\right]\right\} \tag{1}$$

where Y - longitudinal and transverse adhesion coefficient, D, C, B, E – some constants obtained experimentally, and x – the sliding parameter depending on different conditions, respectively [31, 32].

Let us present some part of the results of data processing in the longitudinal direction (Table 1) at a slip angle of 0 degrees and its evaluation in divergence from the evaluation.

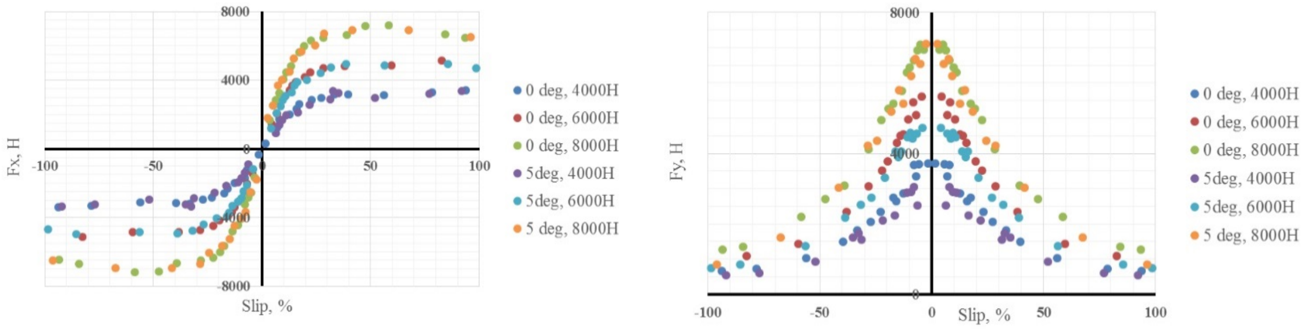


a b



c

Fig. 4. Experimental diagrams of the variation of adhesion coefficients from sliding. a – R_z 4000H, b – R_z 6000H, c – R_z 8000H



a

b

Fig. 5. Experimental graphs of changes in longitudinal (Fx) and lateral (Fy) forces from sliding at different vertical loads and slip angles

Table 1. Experimental and approximating Pacejka data

4000 H				6000 H				8000 H			
A	B	C	D	A	B	C	D	A	B	C	D
0.85	1.5	0.00006	1	0.8	1	0.0003	4	0.8	1	0.0002	6
S	φx (ex.)	φx (apr.)	Div. %	S	φx (ex.)	φx (apr.)	Div. %	S	φx (ex.)	φx (apr.)	Div. %
-93.8	-0.82	-0.803	-2	-82.6	-0.8	-0.787	-1.59	-84.3	-0.766	-0.788	2.926
-56	-0.86	-0.848	-1.59	-38.1	-0.76	-0.746	-1.71	-58.45	-0.78	-0.775	-1.01
-22.9	-0.735	-0.716	-2.68	-10.4	-0.477	-0.461	-3.4	-19.36	-0.651	-0.636	-2.231
27.3	0.77	0.769	-0.34	14	0.579	0.552	-4.745	17.29	0.63	0.608	-3.494
39.6	0.825	0.838	1.62	28.3	0.727	0.71	-2.364	39.14	0.752	0.748	-0.411
78.4	0.86	0.823	-4.34	59.5	0.793	0.776	-2.124	47.42	0.771	0.764	-0.91

Graphs of the obtained approximating functions are shown in Fig. 6.

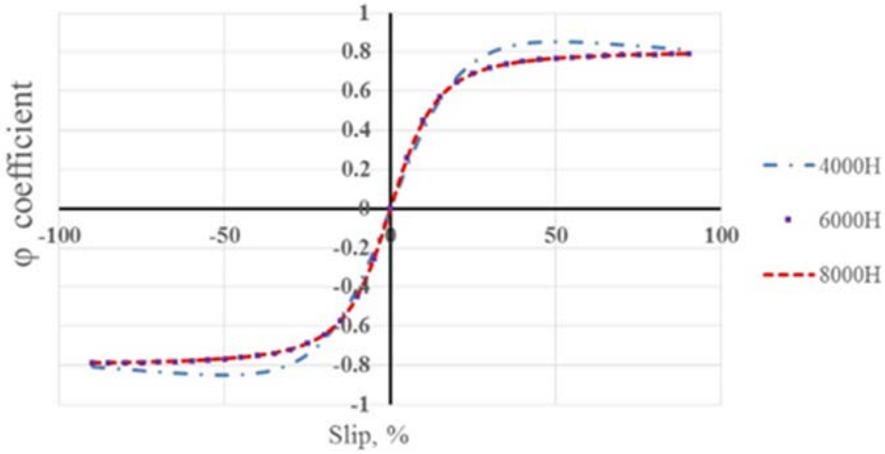


Fig. 6. Graphs of approximating Pacejka functions $\varphi_x(S)$

4 DISCUSSION

Numerical values presented above were obtained by testing the tire on asphalt pavement with a high adhesion coefficient (0.6–0.8), which is a prerequisite for research and certification work to assess the handling and stability of the vehicle, as well as the work of the electronic stability control and other "electronic helpers". Thus, in the case of scientific research in the field of ABS systems, and an assessment of anti-skid properties on roads with a low adhesion coefficient, it is necessary to conduct similar studies on different types of surfaces (ice, wet asphalt, packed snow, basalt surface, etc.).

Pacejka's first publications were first published in 1987 and 1989 [3], and it quickly gained popularity in creating tire models to calculate steady-state forces and moments under various sliding conditions. A typical application is vehicle control studies. This model is clear and very easy to implement. However, with all the advantages, there are also negative aspects. The problem is that the "magic formula" simulation is ambiguous at low speeds, which limits the range of numerical calculations. This is due to the lack of a derivative in zero, which leads to "stagnation zones" and the loss of singular solutions. In this regard, researchers continue to look for other mathematical apparatuses.

The obtained functional dependencies are used in modeling the dynamics of vehicle movement. We have obtained the theoretical approximating function provides convergence to the experimental result within 5%, which is acceptable in engineering practice. A competently assembled approximated tire model file will have a positive effect on the convergence of the object motion dynamics experiment with the simulation [33].

5 CONCLUSIONS

This research aims to develop a verified mathematical model of the PAC2002 light commercial vehicle tire, which was eventually accomplished.

In the course of this research, Russian specialists solved a number of problems: developed a measuring unit and methodology of road tests, conducted a full-scale experiment, and successfully processed and summarized the measured data in the PAC2002 file. In this article, the basic principles in the preparation, implementation, and analysis of the study of the wheel interaction with the bearing surface were reviewed and outlined.

It is worth noting that this study was performed as part of a more significant HIL-simulation of the dynamics of a light commercial vehicle equipped with ESC systems. The resulting PAC2002 parameter file was successfully integrated into the vehicle curvature model, thereby successfully improving the convergence of the overall dynamics simulation [25, 34].

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