Experimental research of the directional stability characteristics of a passenger car when moving around

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Abstract. The determination of lateral skid features of passenger car according to road experiment data, with the use of modern diagnostic equipment is described. As the model of a single vehicle with a driven front axle (Bicycle and planar – 4-wheel) used for the comparative analysis of indicators of stability of motion. The stages of the experiment and processing order of received results are shown. The article describes the definition of the characteristics of the wheel lateral withdrawal of a passenger car according to a road experiment using modern diagnostic equipment. The stages of the experiment and the processing order of the results are shown.

Formulation of the problem
The directional stability of a car moving at high speed on the road is one of the main operational properties that affect the safety of vehicle movement. Safety requirements are most relevant in modern European society.

An analysis of recent studies [1], [2] indicates the possibility and need for further study of the stability indices of curvilinear motion. Promising results were obtained using a simple tool. Research should continue, complicating the measuring equipment.

The purpose of the study is to obtain indicators of directional stability of the movement, in the conditions of the real mode of movement of the wheeled vehicle in a circle.

During the test, the tasks of comparing the parameter values obtained in two ways were performed:
- measurement with the Tech-2 diagnostic tool (Fig. 1);
- measurement of source data with simple tools, followed by calculation of values according to the model;
- In addition, the values of the parameters obtained by measuring with the Tech-2 device and determined by formulas that relate some parameters were compared among themselves.

The experiment used an Orel Zafira car released in 2002.
Figure 1. General view of the Tech 2 device (a) and the connection diagram to the on-board computer 1 – power supply; 2 - connection sockets for connecting the Tech 2 device; 3 - electronic control unit connector.

Figure 2. The platform for the experiment with the Opel Zafira car. a) the movement of an experimental vehicle based on Opel Zafira in accordance with the marking of the corridor of movement b).

The surface of the test site is horizontal and has a measured roughness value of 1.4 - 2.0 mm (according to the “sand spot” method, which allows a marginal measurement error of 0.01 mm).

The car was driven by an experienced driver.

According to the plan of the experiment, the car moved around circles of different radii; trajectories of movement of the middle of the front and rear axles were determined using hydraulic and powder markers (Fig. 3).

Before the experimental study of Opel Zafira car underwent diagnostic and adjustment work at the Opel workshop. The technical condition of the running gear and suspension corresponded to the technical requirements. The car used tires 195 / 55R15.

Below the progress of the experiment and its results are depicted. The scheme of the mathematical model that was adopted in the study is shown in Fig. 4 [6].

To solve research problems, movement was carried out in two circles (i = 2) of arbitrary small radii (Ri-const), the immutability of which was controlled by a constant value of the angle of rotation of the
steering wheel (measured by the Tech-2 diagnostic device. A fragment with the results of measurements expressed by the device is shown in Table 1.

The total number of measurements (while moving in one circle) was 77 units with the same time period between adjacent measurements.

The angle of rotation of the steering wheel remained unchanged - 252 degrees (column 4), which corresponds to a rotation angle of the “average” steering wheel of the model by \(19.4^\circ\).

![Image](image-url)

*Figure 3. The trajectories of the centers of the front and rear axles of the car with a measuring tape-line*

![Image](image-url)

*Figure 4. The kinematic diagram of the stationary motion of a passenger car bicycle model in a circle:*

\(\theta^*\) - is the angle of rotation of the front wheel; \(\delta_1\) and \(\delta_2\) – are the angles of the front and rear wheels; points A, B and C indicate, respectively, the centers of the front, rear wheels and the center of mass of the model; point D is the intersection of the perpendicular to the longitudinal axis (R) and the axis itself (AB); point M is the instantaneous center of velocity; VA, VB, VC and VD: linear speeds of points, respectively, A, B, C, and D; 1, 2 and 3 – trajectories of turns, respectively, of the centers of the front, (point A) and rear axles point (B), as well as the center of mass (point C)
To evaluate the driving stability, it is necessary to accurately determine the speed of the center of mass of the car, and the device measures the linear speeds of each of the two rear and front wheels separately (internal and external when moving in a circle). In order to justify the formula for calculating the speed of the center of mass of the wheeled vehicle, the following scheme was considered (Fig. 5).

The segment AB depicts the case of a bicycle model. The linear longitudinal speeds of the inner and outer rear wheels are, respectively, equal to:

\[ V_{21}^* = V^* - \omega^* \cdot \frac{H_2}{2}, \]
\[ V_{22}^* = V^* + \omega^* \cdot \frac{H_2}{2}. \]  

(1)

It should be noted that for all 77 measurements, the inequality \( V_{22} > V_{21} \) is observed, and the difference \( (V_{22} - V_{21}) = 3 \) km/h is traced; only in 16 measurements out of 77 it has a different meaning: 1 time - 2 km/h, 15 times - 4 km/h.

Table 1. Tech-2 measurement results.

| Measurement number | Lateral acceleration, \( a_y \), m / s² | Angular velocity, \( \omega^* \), deg / s (rad / s) | Steering angle, \( \theta_p \), deg | The speed of the rear wheels, km / year (m / s) | Inner to Turn, \( V_{21} \) | Turn-by-turn, \( V_{22} \) |
|-------------------|----------------------------------------|-----------------------------------------------|---------------------------------|---------------------------------|-----------------|-----------------|
| 1                 | 2                                      | 3                                             | 4                               | 5                               | 19 (5.28)       | 22 (6.11)       |
| 2                 | 3,5                                     | 30 (0.525)                                   | 252                             | 18 (5.00)                       | 21 (5.83)       |                 |
| 3                 | 2,7                                     | 29 (0.438)                                   | 252                             | 18 (5.00)                       | 21 (5.83)       |                 |
| 4                 | 2,5                                     | 29 (0.438)                                   | 252                             | 18 (5.00)                       | 20 (5.56)       |                 |
| 5                 | 3,1                                     | 30 (0.525)                                   | 252                             | 18 (5.00)                       | 21 (5.83)       |                 |
| 6                 | 3,1                                     | 29 (0.438)                                   | 252                             | 18 (5.00)                       | 21 (5.83)       |                 |

Figure 5. The kinematic scheme used to determine the projections onto the segment AB of the speeds of point B and the center of mass of the car: \( \vec{V}_{21}^* \), \( \vec{V}_{22}^* \) - linear speeds, respectively, of the inner and outer rear wheels (during a turn); \( \vec{V}^* \) - the projection of linear velocities on the segment AB, which corresponds to the movement in a circle; H1 and H2 - track, respectively, of the front and rear wheels; \( \omega^* \) - is the angular velocity; A, B and C are points indicating, respectively, the middle of the front and rear axles, as well as the center of mass.
Thus, the linear longitudinal velocity of the center of mass should be calculated by the formula:

\[ V^* = \frac{V_{21}^* + V_{22}^*}{2} \]  

(2)

The indicated interpretation is correct if there is no slip in the contact patch of the rear wheels with the supporting surface, which can be admitted taking into account the fact that the rear wheels of the car that is being tested are driven. The conditions for measuring speed for the front drive wheels are given below, after analyzing the data measured with the rear wheels.

The reliability of the parameter values measured by the diagnostic tool, given in table 1, can be checked if appropriate mathematical dependencies are used [4].

The angular velocity of rotation relative to the vertical axis passing through the center of mass is calculated by the formula:

\[ \omega^* = \frac{V_{22}^* - V_{21}^*}{I_2} \]  

(3)

which will be absolutely true for the case of a complete absence of sliding in the contact.

Lateral acceleration is determined by the following formula:

\[ a_y = V \cdot \omega^* = \frac{V_{22}^* + V_{21}^*}{2} \cdot \frac{V_{22}^* - V_{21}^*}{H_2} = \frac{v_{22}^2 - v_{21}^2}{2H_2}. \]  

(4)

![Graphs](image)

**Figure 6.** Dependences of lateral acceleration of the center of mass of the vehicle (a) and angular velocity (b) on time indicated by conventional values:

1 – graph based on measured data; 2 – graph based on calculated data.

Two factors can very much affect the degree of coincidence of the measured and calculated values of lateral acceleration: sliding in the reference contact and the presence of acceleration of the lateral velocity projection. The latter will change the calculation formula (4) to the following

\[ a_y = u + V \cdot \omega. \]  

(5)
If $u \neq 0$, then there were violations of the manual control system.

Below, Figure 6 shows the dependences of lateral acceleration of the center of mass of the vehicle and angular velocity on time when moving the vehicle in a circle, which corresponds to a rotation of the steered wheel by an angle of $19.4^\circ$.

Visual analysis of the graphs allows us to conclude that the oscillation directions of graphs 1 and 2 coincide. The scattering of the measured and calculated curves for acceleration coincide. As for the angular velocity, the calculated graph has significantly larger amplitude fluctuations than the measured graph [5]. The statistical indicators for the measured and calculated values are determined and given in Table 2.

| The angle of the wheel rotation, deg. | Parameter Name          | Average, $\bar{a}$ | Standard deviation | The coefficient of variation |
|-------------------------------------|-------------------------|--------------------|--------------------|-----------------------------|
| 19.4                                | Lateral acceleration, m/s$^2$ | measured 4.0052    | 0.6649             | 0.1660                      |
|                                     |                         | estimated 3.7246   | 0.6601             | 0.1772                      |
|                                     | Angular velocity, rad/s | measured 0.5705    | 0.0346             | 0.0606                      |
|                                     |                         | estimated 0.5952   | 0.0782             | 0.1314                      |
| 14.8                                | Lateral acceleration, m/s$^2$ | measured 4.2827    | 0.8044             | 0.1878                      |
|                                     |                         | estimated 4.0886   | 0.8765             | 0.2144                      |
|                                     | Angular velocity, rad/s | measured 0.4991    | 0.0303             | 0.0607                      |
|                                     |                         | estimated 0.5263   | 0.0951             | 0.1807                      |

Small values of the coefficients of variation indicate a significant probability of the normal law of distribution of parameters. For lateral acceleration, the variances for the data of the measured and calculated statistical series are uniform. The experimental value of the Fisher criterion is $F_{\text{exp}} = 0.6649 / 0.6601 = 1.01$, which is less than its tabular value, $F_{\text{tab}} = 1.53$.

In the case of evaluating the homogeneity of similar variances of angular velocity, the opposite result is that the variances are heterogeneous ($0.0782 / 0.0346 = 2.26 > 1.53$).

According to the statistical data, an interval estimate is determined, which allows us to determine the accuracy of $\delta$ for a given confidence level of measurement and calculation of lateral withdrawal [3]. Probability $\gamma$ is assumed that the interval $(\bar{a}_v - \delta, \bar{a}_v + \delta)$ containing (covers) an unknown parameter value equal to 0.95. Then, the accuracy of the estimate is:

$$\delta = \frac{t \cdot \sigma}{\sqrt{n}},$$

where $n$ - is the sample size;
$t$ - the number (argument) to which the value of the Laplace function corresponds, equal to $\gamma / 2$.

Then the Laplace function $\Phi(t) = 0.475$ and, in accordance with the table [3], $t = 1.96$.

Thus $\delta = \pm 0.147$ m / s$^2$. In this case, the relative error is 4%.

**Conclusions**

Indicators of directional stability of motion obtained using Tech 2 in the conditions of a real mode of car movement in a circle. A comparative analysis of the experimental data and those obtained by modeling the motion of the vehicle gave uniformity of the output values. The results indicate the need for additional measures to ensure stationary traffic.
References

[1] Verbitskii V G, Makarov V A and Kuliev R A 2007 On the approach to determining the parameters of tire deflection during stationary movement of a passenger car around a circle (Ukraine Makeevka Bulletin DonNASA) chapter 5 (67) pp 106-111.

[2] Verbitskii V G, Makarov V A and Kostenko A V 2008 Experimental evaluation of the parameters of the lateral withdrawal of the axles of a passenger car during its stationary movement around a circle (Ukraine Donetsk Bulletin DIAT) chapter 4 pp 40-45.

[3] Gmurman V E Probability theory and mathematical statistics 1972 Moscow Hig. school P 368

[4] Verbitskii V.G. Makarov V A and Volokhov A S 2007 Building a mathematical model of a passenger car with consideration for the mutual influence of longitudinal and transverse forces in the wheel contact spot (Ukraine Donetsk Bulletin DIAT) chapter 4 pp 38-43.

[5] Makarov V A, Bondarenko A E, Volokhov A S and Kuplinov A V 2012 On the issue of determining errors in the experimental study of vehicle stability (Ukraine Luhansk Bulletin V Dahl EUUN) No. 9(180) vol 1 pp 131-136.

[6] Verbitskii V G, Sakhno V P and Makarov V A 2004 Influence of the asymmetry of cornering forces on the static stability of two-axle vehicle International Applied Mechanics No. 11 pp 1304-1309.