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Vidas ŽURAULIS
Edgar SOKOLOVSKIJ
Jonas MATIJOŠIUS

THE OPPORTUNITIES FOR ESTABLISHING THE CRITICAL SPEED OF THE VEHICLE ON RESEARCH IN ITS LATERAL DYNAMICS

MOŻLIWOŚCI OKREŚLENIA PRĘDKOŚCI KRYTYCZNEJ POJAZDU NA PODSTAWIE BADAŃ JEGO DYNAMIKI POPRZECZNEJ

In this paper, the parameters important for lateral dynamics of vehicles are analyzed in order to establish the values of its critical speed on the moment of losing the stability. The values of the vehicle's speed yaw rate, the steering wheel angle, the lateral acceleration, and the roll angle obtained from experimental tests are filtered according to the set conditions and only the general values that mean the beginning of the vehicle slipping are selected. For more precise assessment of the selected values, a statistical analysis is carried out. The Normal distribution law describes scattering of the selected values in the most relevant way and concretizes the critical speed being established. In the end of the paper, the obtained values of the speed are compared to the results of the theoretical calculations. Conclusions assessing the developed technique of selection of the parameters are provided.

Keywords: *critical speed, lateral dynamics, vehicle sideslip, stability, circular motion.*

Niniejsza praca analizuje parametry istotne dla dynamiki poprzecznej pojazdów w celu ustalenia wartości prędkości krytycznej w momencie utraty przez nie stabilności. Wartości szybkości zboczenia przez pojazd z kursu, kąta skrętu kierownicy, przyśpieszenia poprzecznego oraz kąta odchylenia się pojazdu, uzyskane w badaniach doświadczalnych, dobrano pod kątem założonych warunków i tylko ogólne wartości oznaczające początek poślizgu pojazdu zostały wybrane. W celu dokładniejszej oceny wybranych wartości przeprowadzono analizę statystyczną. Prawo rozkładu normalnego opisuje odpowiednie rozproszenie wybranych wartości i konkretyzuje ustaloną prędkość krytyczną. W końcowej części pracy porównano uzyskane wartości prędkości z wynikami obliczeń teoretycznych. Wnioski służą ocenie opracowanej techniki doboru parametrów.

Słowa kluczowe: *prędkość krytyczna, dynamika poprzeczna, poślizg pojazdu, stabilność, ruch obrotowy.*

1. Introduction

Assessment of parameters of vehicles became a topical and permanently disputable object for persons involved in creation and improvement of vehicles and, of course, all traffic participants as early as since their appearance on roads. Each of the above-mentioned categories has its own goals, namely: striving for technological progress; ensuring safe and reliable exploitation; adaptability to various situations of the daily life to the maximum possible extent. Modernity of today vehicle systems and the possibilities of their diagnostics enable to carry out a detailed exploration of various parameters of movement that become important in improving the safety systems, in investigation of traffic events or upon striving to clear up (upon the maximum accuracy) the regularities of movement of a vehicle, as a totality of aggregates with different properties. A moment of losing control of a vehicle may be identified as a critical value of speed that may be found upon applying various methods. If all the systems are precisely assessed and mathematically described, an application of the numerical method for estimating the parameters is possible; however, it requires a particularly detailed technique for application of fundamental knowledge and often is too complicated for many cases of establishment. So, experimental tests are used for estimation of certain regularities upon real conditions.

On investigation of the parameters of lateral dynamics of a vehicle, a model of a vehicle with four degrees of freedom is most frequently used. Such a model assesses the key parameters and does not charge the calculations with data of low importance. The calculation technique based on the said model takes into account the loads onto the wheels and the nonlinearity of the tires and it enables to calculate the lateral forces acting the tires and the sideslip angles [1] and [5]. Longitudinal and lateral speed estimation is often used from vehicle cornering stiffness, friction parameters in various driving maneuvers [20]. Chinese scientists apply methods of analysis to data collected from sensors in order to introduce the earlier developed algorithms in active safety systems of vehicles. The interaction between the tire and the road dependently on the speed and character of driving is analyzed. For the research, experiments, mathematical models and computer programs, are used [8].

Lateral stability of a vehicle depends not only on the acting lateral forces, but on the longitudinal dynamics as well. Sideslip in vehicle usable in auto racing is formed artificially by the parking brake or by considerable increasing the tractive force of driving wheels. The performance parameters of such movement and the algorithms usable for their processing were explored by scientists of Switzerland and USA in 2010 [18]. The surface of the road where the vehicle is moving distinguishes itself for the type of the pavement, unevenness and geometrical parameters, thus the road parameters considerably impact the general dynamics of the vehicle [16].

At Heudiasyc laboratory (France), the investigations on the sideslip angle of a vehicle dependently on the acting lateral forces in case of a sudden turn were carried out [15]. On double late change and slalom maneuvers upon the lateral acceleration up to 4 g, the results of experiments and mathematical simulation differed inconsiderably; however, when lateral acceleration exceeded 0.6 g, the results became markedly different because of nonlinearity of tires that's assessment required special investigation in each case.

On expert's examinations of traffic events, various cases of traffic events, such as collisions of vehicles [12], hitting a pedestrian [19], turning turtle [13], collisions with obstacles [14] and so on, are examined. If sideslip of wheels takes place on a traffic event, it is very important to estimate precisely the lateral dynamics parameters of adherence of the wheels with the pavement and to establish the initial moments of losing the stability and critical speed [3] and [13].

Operation of electronic stability systems (ESP) is based on control of the intensity of the rotational speed of the body, angular rotational speeds of wheels and the acting accelerations. According to the data from the sensors, the established processing algorithm assesses a stability of the vehicle and, when required (when the limit of stability provided by the manufacturer is overstepped), sends signals to the control systems [7] and [10]. In critical stability cases, operation of the traction system and the vehicle braking system is very important, so activation of the said systems on the proper moment is a matter of a great relevance [21].

2. Vehicle model

Analysis of the dynamics of a vehicle moving along a circular trajectory is convenient upon using a model with four degrees of freedom (DOF) (Fig. 1). This mathematical model provides a possibility of vehicle body longitudinal and lateral movement, yaw (ψ) and roll (φ) movement. In Fig. 1, v_x and v_y are the longitudinal and lateral components of the speed vector, respectively, in the point A that is the center of mass of the vehicle plane's projection. On the vehicle standing or uniform rectilinear movement, the center of mass is leant at the angle θ in respect of the point B. This leaning is caused by the position of the axis of inclination that, in its turn, is impacted by the structure of the vehicle's suspension. On turning, the lateral force acting upon the vehicle causes a rotation of the sprung masses (m_s) at the angle φ around the said axis. In the presented model, the steering angles $\delta_{1,2}$ and sideslip angles $\alpha_{1,2,3,4}$ of all wheels are shown as well. C is the center of mass on low-speed turning of the vehicle at the radius R' without sideslip, and C' is the momentary center of mass on turning at a larger angle R' with a higher speed. In such a case, the tire planes differ from the directions of the speed vector $v_{1,2,3,4}$ by angles $\alpha_{1,2,3,4}$.

According to Lagrange's equation, the equations of motion for 4-DOF vehicle model are derived:

$$
\begin{aligned}
&m\left(\dot{v}_x-\dot{\psi}v_y\right)+m_s\left(h'\varphi\ddot{\psi}+2h'\psi\dot{\varphi}\right)=F_{1x}\cos\delta_1+F_{2x}\cos\delta_2-F_{1y}\sin\delta_1-F_{2y}\sin\delta_2-F_{xd};\\
&m\left(\dot{v}_y+\dot{\psi}v_x\right)-m_s\left(h'\ddot{\varphi}-h'\dot{\psi}^2\varphi\right)=F_{1x}\sin\delta_1+F_{2x}\sin\delta_2+F_{1y}\cos\delta_1-F_{2y}\cos\delta_2+F_{3y}+F_{4y};\\
&I_z\ddot{\psi}+\ddot{\varphi}\left(I_z\theta-I_{xz}\right)-m_sh'\varphi\left(\dot{v}_x-\dot{\psi}v_y\right)=F_{1x}\sin\delta_1a+F_{2x}\sin\delta_2a+F_{1y}\cos\delta_1a-F_{2y}\cos\delta_2a+\\
&+M_{1z}+M_{2z}-F_{3y}b-F_{4y}b+M_{3z}+M_{4z}+F_{1x}\cos\delta_1s_1-F_{2x}\cos\delta_2s_1-F_{1y}\sin\delta_1s_1-F_{2y}\sin\delta_2s_1;\\
&\ddot{\varphi}\left(I_x+m_sh'^2\right)+m_sh'\left(v_y{}^2+\dot{\psi}v_x\right)+\ddot{\psi}\left(I_z\theta-I_{xz}\right)-\varphi\dot{\psi}^2\left(m_sh'^2+I_y-I_z\right)+\\
&+\dot{\varphi}\left(k_{\varphi1}+k_{\varphi2}\right)+\varphi\left(c_{\varphi1}+c_{\varphi2}\right)-\varphi m_sgh'=0.
\end{aligned}
\tag{1}
$$

where: m – total mass of the vehicle, m_s – sprung mass, F_x – tractive forces, F_y – lateral forces, F_{xd} – aerodynamics and rolling resistance forces, I_x, I_y, I_z – moments of inertia around x, y and z axes, I_{xz} – inertia product of the sprung mass, M_{iz} – self-aligning moment generated by wheel i, R and R' – radius of the cornering vehicle, moving without sideslip and with sideslip, s_1 and s_2 – distances from the center of gravity to the front and rear wheel, a and b – distances from the center of gravity to the front and rear axle, h' – arm length of roll moment, $c_{\varphi1,2}$ – roll stiffnesses of front and rear exes, $k_{\varphi1,2}$ – damping coefficient of front and rear exes.

3. Experimental procedure

On a natural test, the vehicle is involved in circular movement at the agreed diameter upon gradual increasing the speed up to the limit when following the trajectory becomes impossible because of sideslip. Such a test is not classified as steady-state circular test, because the speed is changed. In addition, the driver is provided a freedom in correction of the steering wheel angle for maintaining the agreed circular trajectory of movement. A test of such a type was described in the international standard ISO 4138 [9]. In addition to circular movement of the constant radius, the standard also provides research techniques for cases when constant steering wheel angle and constant speed are kept.

On the tests, the ability rating of the vehicle Toyota Avensis is fixed by the equipment mounted on its sprung masses, namely: a triaxial $\pm 3g$ accelerometer and a ± 150 deg/s gyroscope mounted on the windscreen of the vehicle; a noncontact optical speed sensor Correvit S-350 Aqua in front of the vehicle (Fig. 2a); three laser sensors HF-500C for measuring the pitch and roll angles of the body; and a wire potentiometric steering wheel angle sensor Kuebler D8 for steering wheel angle measurement. For the tests, a closed 80 m long and 60 m wide site with asphalt concrete pavement was used.

Drives are carried out along a circular trajectory with the radii of 10, 15 and 20 metres, respectively; each test is repeated at least for four times. In such a way, it is tried to avoid possible gross errors of measurement.

During the experiment, information from the sensors is fixed by the data collection equipment Corrsys-Datron DAS-3 (Fig. 2b.) and later is processed in the general time scale by software *TurboLab 6.0*. Data collection and graphical presentation during the tests is provided in Fig. 3.

4. Analysis of experimental data

For a detailed analysis, the most varying parameters on curved trajectory were selected: the vehicle speed, the yaw rate, the steering wheel angle, the lateral acceleration, and the roll angle. Although all above-listed parameters are measured directly during the tests, the target value, i.e. critical speed, is a complex result of

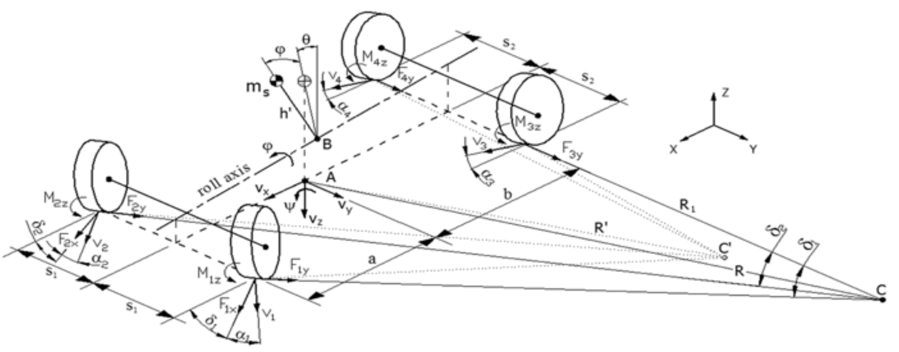
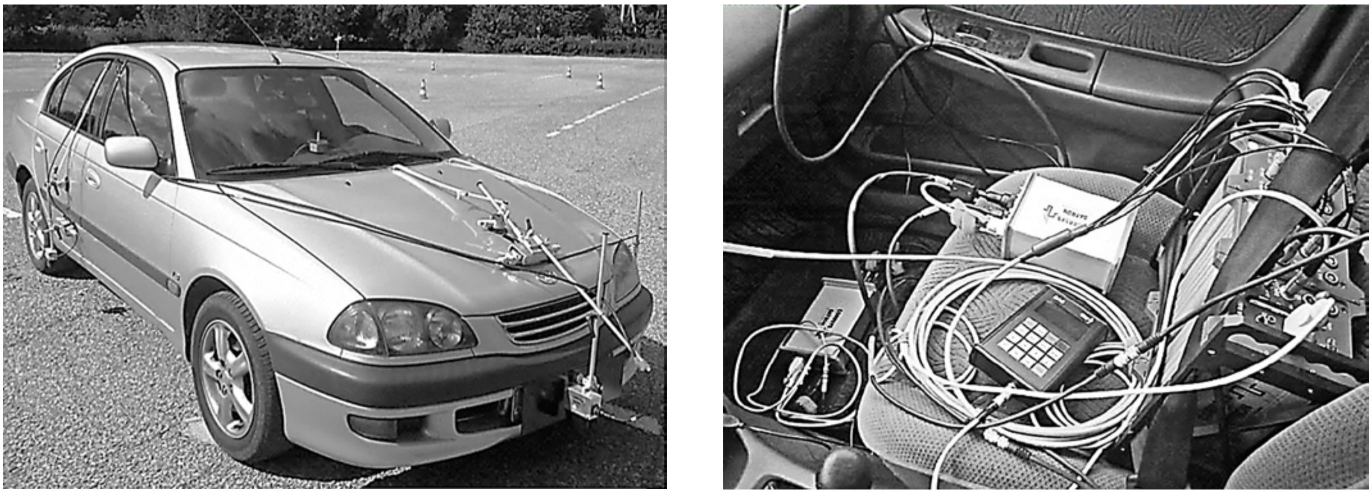
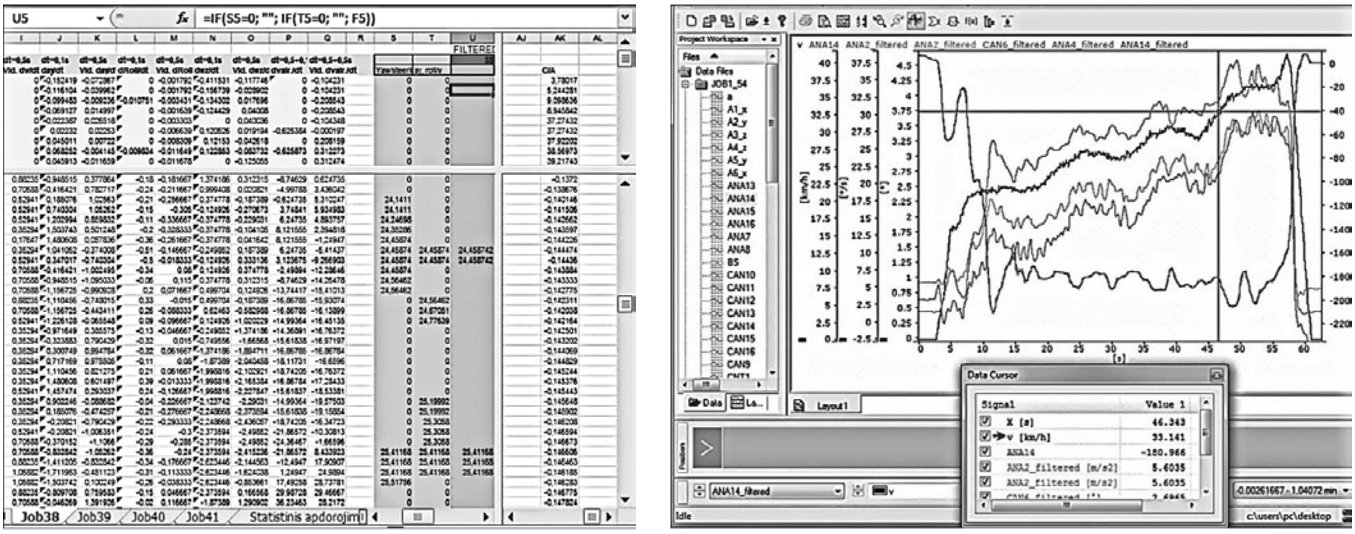


Fig. 1. 4-DOF vehicle model



a) b)

Fig. 2. Equipped vehicle during experimental procedure



U5 =IF(S5=0; ""; IF(T5=0; ""; F5))

Data Cursor

Signal	Value 1
☑ X [s]	46.343
☑ v [km/h]	33.141
☑ ANA14	-180.966
☑ ANA2_filtered [m/s2]	5.6035
☑ ANA2_filtered [m/s2]	5.6035

a) b)

Fig. 3.Data selection during experimental procedure: a) data window of numerical form, b) window of signal analysis in TuboLab 6.0 software

the measurement that is obtained upon applying additional methods of analysis. A complex measurement is considered establishing the values of parameters of the same character by measuring various indirect parameters or their dependences. Therefore, obtaining the optimal result it is necessary to evaluate the overall parameter changes over time combining them as much as possible.

In order to establish the critical speed according to the parameters fixed during the tests, a special filter is formed. Generated selection model separates moments corresponding to moving in critical speed:

1) the conditions of sideslip of the vehicle according to the intensity of the yaw and the steering wheel angle change:

$$\begin{cases} \dfrac{d\dot{\psi}}{dt} > 0; \\ \dfrac{d\delta_v}{dt'} \le 0; \end{cases} \tag{2}$$

$$\begin{cases} \dfrac{d\dot{\psi}}{dt} < 0; \\ \dfrac{d\delta_v}{dt'} \ge 0. \end{cases} \tag{3}$$

Here the first part of the condition (2) selects preliminary moments of slipping when the intensity of the yaw rate of the vehicle upon no change of the steering wheel angle or its reducing. To such cases of slipping, oversteering is attributed. The second part of the condition (3) selects expectable moments of slipping when the steering wheel angle is not changed or increased and the vehicle turns less and less. It is considered that understeering takes place;

2) the condition of sideslip of the vehicle according to the lateral acceleration that affects the vehicle and the roll angle intensity dependently on the longitudinal acceleration:

$$\begin{cases} \dfrac{da_y}{dt} < 0; \\ \dfrac{d\varphi}{dt} < 0; \\ \dfrac{dv}{dt} \ge 0. \end{cases} \tag{4}$$

where: $dt \in [t_i; t_{i+5})$, $dt' \in [t_i + t_{vr}; t_{i+5} + t_{vr})$.

In this group of conditions (4), the moments when upon maintaining a constant speed of circular movement or its increasing, the limit of

*Table. 1. The statistical series of the selected values of speed according to the data on circular movement**

Range, *v*, km/h	15–20	20–25	25–30	30–35	35–40	40–45	45–50
Frequency, m_i	1	22	77	53	28	3	0
Statistical probability, p_i	0,005	0,120	0,418	0,288	0,152	0,016	0,000
$\sum p_i$	0,005	0,125	0,543	0,832	0,984	1,000	1,000

**** at the radius of 15 meters***

adhesion of the wheels with the road surface is overstepped and the acting lateral acceleration and lateral angle of inclination of sprung masses becomes less.

The specified dependence *dt* covers the interval with five measurement points. In the specific case, it means 0.5 s, because the frequency of general registration of parameters is 10 Hz. So, a 0.5 s interval is accepted for examination of variation of a relevant parameter and within such an interval, a remarkable character of variation of a certain parameter may be assessed. The interval dt' provided at the parameter of steering wheel angle δ_v covers five measurement points as well; however, this parameter is shifted by the value of t_{vr} that means the driver's reaction time to turn steering wheel. According to psychophysiological properties of a driver, the reaction time to turn steering wheel is 1.2–1.4 times longer than the usual reaction time [11]. Taking into account that during the tests, the driver was ready for possible turns of the steering wheel, the said time t_{vr} is not increased on application of selection of critical speed and accepted to be 0.5 s.

After establishing that the parameters satisfy the set conditions, the speed of the vehicle in the beginning of the interval is presented as the result of the selection. It is considered that the conditions are satisfied when the processed parameters satisfy one inequality from the first condition and the inequality of the second condition. Only a measuring line that satisfies the both conditions may be selected.

A variant when $d\dot{\psi}/dt' = 0$ is not included in the conditions of sideslip, because in such a case, slipping is impossible while maintaining a trajectory of constant radius. The case when is not assessed as well, because, in accordance with the preset conditions of the test, on increasing the vehicle speed, the values of a_y and φ will naturally grow (in absence of sideslip) because of centrifugal acceleration.

The moments according to the condition 1 or the condition 2 of sideslip provided in the formulas (2, 3) and (4) are selected in respect of zero, i.e. it is established whether the intensity of the parameter variation was positive or negative. However, striving for more precise identification of the critical speed, optimization of the said values would be convenient. For this purpose, the precise data on the performance of the specified vehicle, including its inertness, lateral stiffness of the tires and stiffness, stiffness and damping of the suspension, are required. However, such a precise assessment would not allow applying the established trend. If a less number of parameters is used for data filtration and a typical scattering of the values of the critical speed is obtained, statistical data processing methods are applied for a further analysis.

5. Statistical processing of the results

After selection of the measurement data according to the formed conditions, scattering of preliminary critical speeds upon certain regularity is obtained. For more precise establishing the target value of speed, the said regularity is assessed upon applying statistical data analysis. In course of establishing the distribution of the selected values of speed, the series of the values is formed first of all and divided into ranges (Table 1). Frequency mi shows the number of values (selected speeds) included in the relevant range and pi shows the statistical probability of appearance of the values in the said range. $\sum p_i$ is integral statistical probability. Statistical processing will make it easier to identify the most commonly recurrent filtered value of critical speed and assess the accuracy of adapted statistical law of distribution.

If the frequency in each interval is known, the average value of the selected speeds is calculated as follows:

$$\overline{T}_{vid} = \sum_{i=1}^{n} T_{V_i} \cdot \frac{m_i}{N} \qquad (5)$$

where: T_{V_i} – the average value of speed in the *i*-th interval, m_i – frequency of access to the range, *N* – the number of selected values of speed. The extent of deviation of the selected values of speed from the average value is calculated as follows:

$$\sigma = \sqrt{\sum_{i=1}^{n} \left(T_{V_i} - \overline{T}_{vid}\right)^2 \cdot \frac{m_i}{N}} \qquad (6)$$

For applying the theoretical distribution law, the relative deflection of the values of speed should be assessed. It is described by the coefficient of variation:

$$v = \frac{\sigma}{\overline{T}_{vid}} \qquad (7)$$

In all analyzed cases (driving along different circles), according to the formed statistical series and calculated performance curves, it was found that $v \le 0.33$ [17]; it means that the selected values of speed are distributed according to the Normal distribution (the Gaussian law) and the shapes of drawn histograms of the distributed values and differential curves f(T) (Fig. 4) preliminary support the statement.

A proper substantiation of the chosen distribution law may be provided upon using the criteria. For reasoning a feasibility of the chosen mathematical model according to all values of the sample, the so called Pearson compatibility criterion χ^2 [4] is most frequently applied. Pearson criterion is based on a comparison of the number of events obtained in empirical way mi with the expected events of the theoretical distribution in the same interval n_{pi}. Upon applying the compatibility criterion χ^2 for verifying the zero hypothesis, the probabilities pi of finding the random variable *H* in the intervals are calculated on the base of a hypothetic function as follows:

$$p_i = P\left(h_{i-1} \le H \le h_i\right) = \int_{h_{i-1}}^{h_i} f(h)dh = F\left(h_i\right) - F\left(h_{i-1}\right) \qquad (8)$$

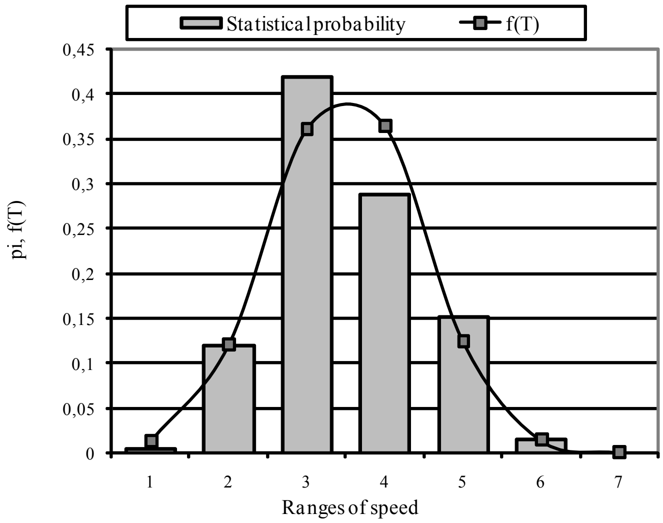


Fig. 4. Histogram and graph of theoretical differential function, R=15 m

where: $i = 1, 2, \ldots, k$ – the numbers of intervals.

On multiplying the calculated probabilities by the sample n, the theoretical frequencies npi of the intervals, i.e. the frequencies expectable if the zero hypothesis is veridical, are found. On the base of the available values, the compatibility criterion χ^2 is calculated as follows:

$$\chi^2 = \sum_{i=1}^{k} \frac{(m_i - np_i)^2}{np_i} \tag{9}$$

The number of the model's degrees of freedom is calculated as follows:

$$v = k - r - 1 \tag{10}$$

where: $k = 7$ – the number of intervals in the formed statistical series, $r = 2$ – the number of parameters of the distribution law under verification: the sample average and dispersion.

According to the level of importance 0.05 and the degree of freedom from χ^2 distribution quantile tables [4], it is found that the critical value $\chi^2_{0.05;4} = 9.488$. The value $\chi^2 = 6.257$ calculated according to the formula (9) is less then $\chi^2_{\alpha;v}$, so the hypothesis that the chosen distribution law duly describes the selected results of the experiment is confirmed. This condition is satisfied for the data on driving along the trajectories of the radius 10 and 20 meters.

On formation of the differential curve *f(T)*, the theoretical probabilities of the applied distribution law are calculated for each interval:

$$f(T) = \frac{A}{\sigma} \varphi_0 \left(\frac{T_{V_i} - \overline{T}_{vid}}{\sigma} \right) \tag{11}$$

where: A – the difference between values of the interval, $A = 5$ km/h, φ_0 – the value to be taken from statistical references.

For finding the probability of critical stability on circular movement of the vehicle with a certain speed, diagrams of the empirical and theoretical functions are drawn (Fig. 5). For a calculation of the integral curve, the following formula is used:

$$F(t) = F_0 \left(\frac{T_g - \overline{T}_{vid}}{\sigma} \right) \tag{12}$$

where: T_g – the value of the end of the statistical series interval, F_o – the value to be taken from statistical references.

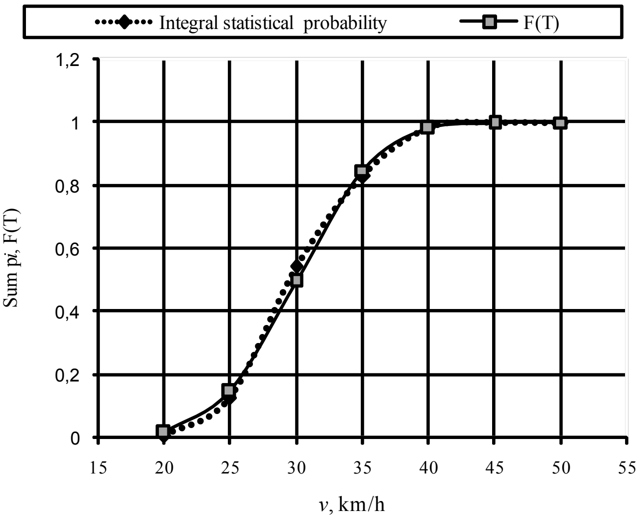


Fig. 5. Graphs of empirical and theoretical function, R=15 m

It may be seen from the diagrams provided in Fig. 5 that starting from approximately 35 km/h, the vehicle moving at the radius of 15 m is prone to sideslip in 90 % of cases. On further increasing the speed, the probability of slipping grows up to almost 100 %.

6. The assessment of the data selection technique

Statistical analysis of the selected experimental values of speed enables a comparison of its results to the results obtained upon applying the methods used in calculations of lateral dynamics of vehicles. In a general case, the lateral force acting in the vehicle center of mass is found as follows:

$$F_y = m \frac{v^2}{R} \tag{13}$$

Then the following equation may be written:

$$m \frac{v^2}{R} = m \dot{v}_y \tag{14}$$

The adhesion coefficient for sideslip, like for longitudinal slip, dependently on the vertical load or as a combined slip effect [6] according to the theory of the circle of adhesive forces:

$$\mu_y = \frac{F_y}{F_z} = \frac{m\dot{v}_y}{mg} = \frac{\dot{v}_y}{g} \tag{15}$$

$$\left(\frac{\mu_x}{\mu_{x,\max}} \right)^2 + \left(\frac{\mu_y}{\mu_{y,\max}} \right)^2 = 1 \tag{16}$$

The value of the speed at the slip that exceeds the limits of friction according to the equation (11):

$$v = \sqrt{\dot{v}_y \cdot R} = \sqrt{\mu_y g R} \tag{17}$$

where: $\dot{v}_y$ – lateral acceleration; μ_y – lateral adhesion coefficient; g – gravitational acceleration.

On comparing the values found according to the formula (17) with the experimental values after their statistical analysis, typical inadequacies are observed. When the normal distribution law was applied in analyzing the movement along the trajectory of the radius of 15 meters, the found average value of critical speed was 30.05 km/h with relative scattering equal to 0.16. If the values of lateral acceleration are selected for a moment of the experiment when the vehicle has lost its stability (the values of speed exceed the established critical value and the trajectory of movement is kept by correction of the steering wheel only), the average value of the critical speed according to the formula (17) is 35.74 km/h. The comparison of the statistically assessed experimental values with theoretically calculated values of critical speed on movement along circular trajectories with the radius of 10, 15 and 20 meters is provided in Table 2.

Table. 2. The experimental and theoretically calculated values of critical speed

Radius of the trajectory of movement *R*, m	10	15	20
The critical speed established by experiments and statistical analysis v_{cr}, km/h	27.86	30.05	35.13
The theoretical critical speed v'_{cr}, km/h	30.57	35.74	42.12
The coefficient for assessing the inadequacies of the established values of critical speed	0.911	0.841	0.834

So, on comparison of the theoretically calculated values of the critical speed with the results of the experiment after their selection and statistical analysis, it was found that the inadequacies of the values for all trajectories involved in the experiment varies between 8.87 % (R = 10 m) and 16.60 % (R = 20 m). For assessing the said inadequacies, the correction coefficients provided in the table 3 may be used.

7. Conclusions

1. The established inadequacies between the theoretically calculated values of the critical speed and the processed experimental values point out that in the activities related to analysis of dynamics of vehicles where fixing of the initial moment of losing a stability by the vehicle is important, an application of the data selection technique developed for the conditions (2), (3) and (4) is purposeful. For simplified calculations, the values of correction coefficients provided in the table 3 may be used. The found inadequacies do not negate the fundamental calculation methods; they only provide an alternative algorithm for assessing the parameters when fixing of the initial moment of losing stability by the vehicle is important.
2. On the established moments of losing stability, it is still possible to stop the slip and to return the vehicle to the desired trajectory by actions of the driver or by active safety systems, so the technique may be useful in the activities related to expert's examination of traffic events, where, in addition to the speed of the vehicle after irreversible losing its control, it is important to identify it's speed when the driver still has technical possibilities to regain its control.
3. The said technique may be used in improving vehicle stability, its active braking and other active safety systems, because sensors installed in electronic systems of modern vehicles may establish the values of parameters that cause increasing efficiency of the systems after processing the values according to the set algorithm.

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Vidas ŽURAULIS, M.Sc.
Edgar SOKOLOVSKIJ, Ph.D., D.Sc., Assoc. Prof.
Jonas MATIJOŠIUS, Ph.D.
Department of Automobile Transport
Vilnius Gediminas Technical University
Basanavičiaus str., 28 LT-03224 Vilnius, Lithuania
E-mails: vidas.zuraulis@vgtu.lt, edgar.sokolovskij@vgtu.lt, jonas.matijosius@vgtu.lt