A new approach to the study of complex vehicle movement during road transport expertise

Ivan Novikov[1], *Andrey* Degtyar[1], *Dmitriy* Lazarev[1,2*], *Nikolay* Zagorodniy[1], *Vitaliy* Makhonin[3]

[1]Belgorod State Technological University named after V.G. Shoukhov, 46 Kostyukova St., 308012 Belgorod, Russia
[2]Expert Forensic Center of the Office of the Ministry of Internal Affairs of Russia for the Belgorod Region, 60 Avenue of Glory, 308000 Belgorod, Russia
[3]Turgenev Orel State University, 95 Komsomolskaya St., 302026 Orel, Russia

Abstract. Road traffic accidents (hereinafter referred to as accidents) are currently a significant problem in the field of road safety in the Russian Federation. In addition to significant material damage, they often entail human losses. In this regard, the issue of investigating an accident is acute, as well as conducting road transport examinations. Modern calculation models do not always allow to determine the mechanism of an accident comprehensively and fully, especially at the final stage of the mechanism, when the vehicle continued its movement after interacting with an obstacle. The task becomes more complicated in cases where the movement of the vehicle did not have adequate calculation models in the specialized literature for specific (particular) cases of movement. Therefore, the construction of a functional universal computational model of complex vehicle movement based on basic physical principles within the framework of road transport expertise is an urgent task.

1 Introduction

The problem of predicting the trajectories of vehicle movement after a complex eccentric impact with another object in modern automotive literature is given very little attention. The study of the parameters of the vehicles movement in these conditions is reduced to a refusal to solve the issue (due to insufficient initial data for calculation or lack of appropriate qualifications from an expert), or to an extremely simplified calculation based on well-known methodological recommendations with certain assumptions. The situation is aggravated by the lack of independence of experts of state institutions in choosing the initial data for calculation, which leads to the lack of an opportunity to approach the solution of this problem in a more flexible form [1].

The solution of this problem can be a specialized software package, such as, for example, PC-Crash. However, the use of this complex does not make it possible to solve all the problems that arise to the expert. For example, traditional calculation methods do not have the ability to take into account a number of factors. For example, the different position of the

* Corresponding author: avtotech31@mail.ru

wheels of the vehicle after impact in relation to their position before it. Also it is necessary to include the case when one or more wheels on the vehicle are missing, blocked or have no internal pressure, and also, due to the deformation of the chassis, the wheels are located in different positions from the standard one. These factors cannot be taken into account by the standard methodology or algorithm of the program [2].

Besides, neither the known methods nor the software systems allow to determine the parameters of vehicle rollover. Especially if we are talking about more than one revolution around horizontal longitudinal or transverse axes, as well as when the car rotates relative to the vertical axis.

It should be noted that in our country, work on expanding the possibilities of calculating non-standard movement of vehicles in the study of road accidents, in addition to the authors of this article, was carried out by other authors. So it is possible to highlight the research of the employees of SPbGASU Evtyukov S.S. and Bryleva I.S. The first conducted a comprehensive study to clarify the speeds of vehicles when hitting low obstacles (for example, curbs), as well as when driving on non-standard surfaces, such as paving slabs, the material of road marking lines, tram tracks, setting the coefficients of adhesion of tires with these surfaces [3]. The second experimentally established the values of decelerations in a number of two-wheeled vehicles [4]. It is also worth noting the work on this topic by V.N. Nikonov [5], who paid great attention to the theoretical explanation of the principle of operation of the CRASH3 algorithm, as well as the work of V.A. Kovalev and co-authors on the problems of aquaplaning [6].

However, these studies are of a particular nature and the construction of an integral model of vehicle movement, taking into account all its design features, road conditions, interaction features within the culmination phase of the incident and the resulting inertial movements before the end of the event of a traffic accident, is currently an urgent problem.

2 Theoretical research

As a rule, a typical solution to the problem of calculating the parameters of a car with a skid (Fig. 1) is reduced to calculating the speed according to a typical formula [14]:

$$V_a = 1{,}8 \cdot j_a \cdot t_3 + \sqrt{26 \cdot \left(j_a \cdot (S_u - L) + j_b \cdot S_{CT} + j_b \cdot L \cdot \frac{\alpha \cdot \pi}{360}\right)} \qquad (1)$$

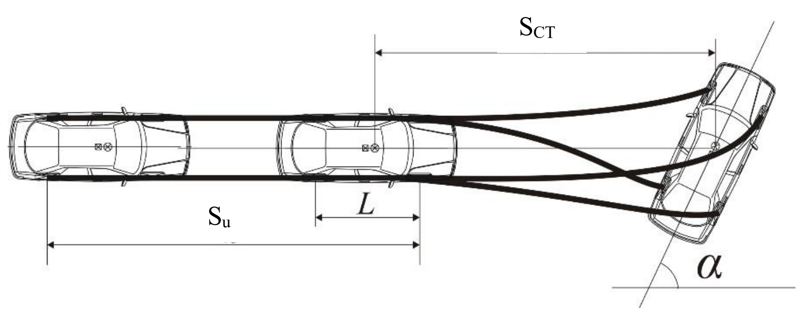


Fig. 1. Stages of the study of functioning effectiveness of automatic fixation systems to ensure road safety.

The study of vehicle rollover is reduced to determining the critical speeds at which skidding is possible [14].

$$V_{zan} = \sqrt{127 \cdot \varphi_y \cdot R} \qquad (2)$$

where φ_y – is a coefficient of transverse adhesion of tires to the road; R – is a turning radius. and this rollover

$$V_{zan} = 3{,}6 \cdot \sqrt{\frac{0{,}5 \cdot B \pm H_c \cdot tg\lambda}{H_c \mp 0{,}5 \cdot B \cdot tg\lambda} \cdot g \cdot R} \tag{3}$$

where H_c – is the height of the center of mass of the vehicle from the road surface; B – is vehicle track; λ – is the angle of the transverse slope of the road.

As for the typical calculation of the vehicle skid parameters described above, its main disadvantage is limited application possibilities. So, using this formula, it is impossible to determine the movement speed of the vehicle before skidding in the event that during the skidding process it made more than one revolution around its center of mass. In addition, parameters such as the number of inertial revolutions, time and, most importantly, the predicted trajectory of the vehicle when using this method for calculation are not available.

The initial solution to this problem was proposed by the authors earlier in the article, where the necessary characteristics of vehicle movement after contact with another object and the corresponding equations of motion were obtained [10].

The shock impulse was determined

$$\bar{S} = -\frac{1+\varepsilon}{G} \cdot (\bar{U}_1 \cdot \bar{n}_1 + \bar{U}_2 \cdot \bar{n}_2) \tag{4}$$

where ε – is the recovery coefficient where ε – is the recovery coefficient; $\bar{U}_1 \cdot \bar{n}_1$; $\bar{U}_2 \cdot \bar{n}_2$ – are projections of vehicle speeds on the corresponding normals; G – is a mass point parameter having a calculation formula

$$G = \frac{m_1 + m_2}{m_1 \cdot m_2} + \frac{h_1^2}{J_1} + \frac{h_2^2}{J_2} \tag{5}$$

where m_1 and m_2 – are the vehicles masses; h_1 and h_2 – are impact levers; J_1 and J_2 – are the moments of inertia of bodies relative to the central axes perpendicular to the plane of motion and passing through the centers of mass.

Each of the above parameters is determined, based on the calculation scheme in Figure 2, by systems of equations

$$\begin{cases} h_1 = x_1 \cdot \sin\alpha - y_1 \cdot \cos\alpha \\ h_2 = -x_2 \cdot \sin(\alpha + \beta) - y_2 \cdot \cos(\alpha + \beta) \end{cases}; \begin{cases} J_1 = \frac{m_1}{3} \cdot (a_1^2 + b_1^2) \\ J_2 = \frac{m_2}{3} \cdot (a_2^2 + b_2^2) \end{cases} \tag{6}$$

where x_1, x_2 and y_1, y_2 – are the coordinates of the impact point relative to the coordinate systems of the centers of vehicles mass; a_1, b_1 and a_2, b_2 – are the corresponding dimensions of the vehicles.

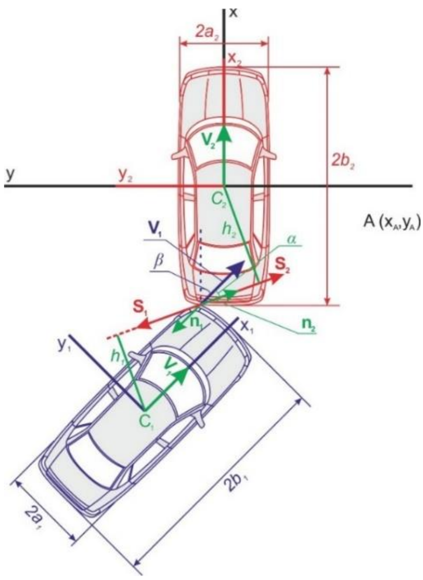


Fig. 2. Calculation scheme of collision of two vehicles.

As a result of transformations, the parameter G is equal to

$$G = \frac{m_1+m_2}{m_1 \cdot m_2} + \frac{3 \cdot (x_1 \cdot sin\,\alpha - y_1 \cdot cos\,\alpha)^2}{m_1 \cdot (a_1^2+b_1^2)} + \frac{3 \cdot [-x_2 \cdot sin(\alpha+\beta) - y_2 \cdot cos(\alpha+\beta)]^2}{m_2 \cdot (a_2^2+b_2^2)} \quad (7)$$

A angular velocities of vehicles after impact

$$\Omega_{1z} = \frac{S \cdot h_1}{J_1}; \quad \Omega_{2z} = \frac{S \cdot h_2}{J_2} \quad (8)$$

A system of equations of motion

$$\begin{cases} m \cdot \frac{dx_{1c}}{dt^2} = \sum F_{kx}^e \\ m \cdot \frac{dy_{1c}}{dt^2} = \sum F_{ky}^e \\ J_c \cdot \frac{d\phi}{dt^2} = 2M_c(\bar{F}_k^e) \end{cases} \quad (9)$$

These equations make it possible to describe the entire process of moving vehicles after contact with the determination of all the parameters of interest to the expert for forecasting and calculating the uncontrolled movement of the vehicle. More complex mechanisms of movement, such as moving with one or more wheels missing or blocked wheels or wheels without internal pressure, etc. are derived from these equations and will be presented in the following papers.

As for the calculation of vehicle rollover, the standard methodology, as mentioned above, is also limited to a narrow range of calculated parameters.

From the standpoint of the postulates of theoretical mechanics, it is possible to create a universal theoretical model for calculating this process, focusing on which it is possible to obtain the necessary parameters for moving a vehicle in the absence of vertical stability. To do this, we will draw up a calculation scheme (Fig. 3).

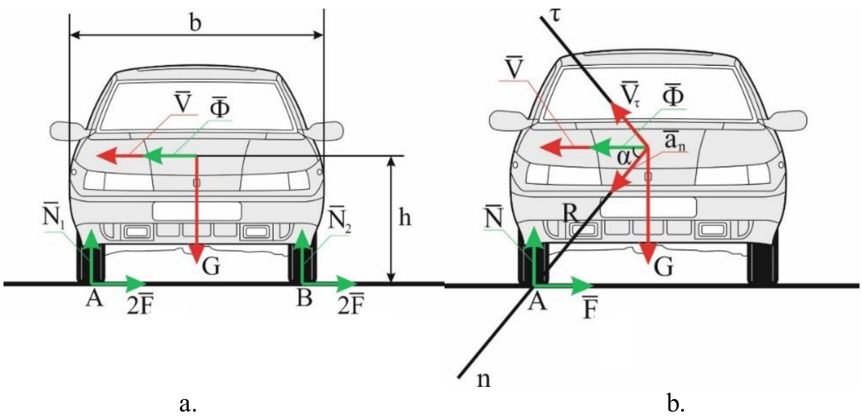


Fig. 3. A calculation scheme for overturning the vehicle.

At the moment of overturning N2 = 0 (Fig. 3a).

To overturn, it is necessary that the body has not yet begun to slide on the surface.

$$F \leq f \cdot m \cdot g \tag{10}$$

where *f* – is the coefficient of friction;

m – is the mass of the vehicle.

It follows from the equilibrium equation (in accordance with the D'Alembert principle)

$$\sum m_a = \Phi \cdot h - G \cdot \frac{b}{2} = 0; \quad \Phi = \frac{m \cdot g \cdot b}{2 \cdot h}; \quad \Phi = m \cdot a \tag{11}$$

where a – is acceleration;

h – is the height of the center of mass.

The rollover condition

$$\Phi \geq \frac{m \cdot g \cdot b}{2 \cdot h} \tag{12}$$

Since there is a slip, it can be assumed that the car begins to rotate around point A (Fig. 3b) as a result of which a number of transformations can be carried out

$$\Phi = m \cdot a_n = m \cdot \frac{V_\tau^2}{R}; \quad R = \sqrt{h^2 + \frac{b^2}{4}}; \ m \cdot \frac{V_\tau^2}{R} \geq \frac{m \cdot g \cdot b}{2 \cdot h};$$

$$V_\tau \geq \sqrt{\frac{g \cdot b \cdot R}{2 \cdot h}}; \ V_\tau = V \cdot \sin\alpha; V \geq \frac{1}{\sin\alpha} \cdot \sqrt{\frac{g \cdot b \cdot R}{2 \cdot h}} \tag{13}$$

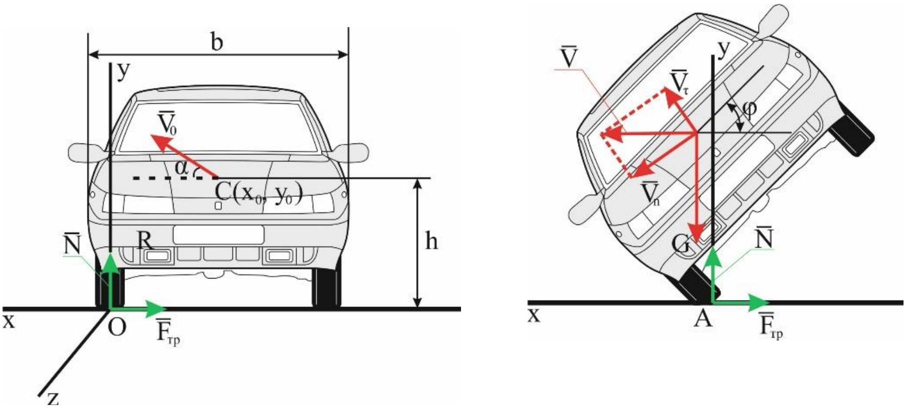
whereV_τ – is the velocity along the axis τ;

R – is the radius of the tipping force.

As a result of the final transformation

$$V_1 \geq \sqrt{\frac{g \cdot b \cdot R^3}{2 \cdot h^3}} \tag{14}$$

With the further movement of the car (Fig. 4a and 4b), let's consider a simple case of motion - the plane movement of the body, i.e. the body moves in the plane of Oxy and rotates relative to the axis Oz



a. b.

Fig. 4. Calculation scheme of vehicle rollover.

Write down the differential equations of motion of the body

$$\begin{cases} m \cdot \frac{d^2x}{dt^2} = \sum F_{kx} \\ m \cdot \frac{d^2y}{dt^2} = \sum F_{ky} \\ m \cdot \frac{d^2\varphi}{dt^2} = \sum m_z(\bar{F}_k) \end{cases} \quad (15)$$

Physically, the plane (surface) does not prevent the body from jumping, i.e. it implements an unstoppable connection. When constructing a mathematical model, an important step is to describe the contact interaction between a body and a plane, since some dynamic effects can only be explained by the presence of friction, while various friction laws can be used: viscous friction, Coulomb friction, etc. At the first stage of solving the problem, let's consider the case in which point A is stationary at the moment of separation. In this case, it is convenient to use differential equations of motion in natural form and make a number of transformations

$$\begin{cases} m \cdot \frac{dV}{dt} = \sum F_{k\tau} \\ m \cdot \frac{V^2}{\rho} = \sum F_{kn} \\ J_z \cdot \frac{d^2\varphi}{dt^2} = \sum M_z(\bar{F}_k) \end{cases} \quad (16)$$

where ρ – is the radius of curvature of the trajectory.

$$m \cdot \frac{dV}{dt} = -G \cdot cos(\alpha + \varphi); \quad tg\alpha = \frac{2 \cdot h}{b}; J_z \cdot \frac{d\omega}{dt} = -G \cdot cos(\alpha + \varphi); \quad J_z \cdot \frac{\omega d\omega}{dt} = -G \cdot cos(\alpha + \varphi);$$

$$\int_{\omega_0}^{\omega_T} \omega d\omega = \int_0^{\pi} -\frac{G}{J_z} \cdot cos(\alpha + \varphi) d\varphi; \quad \frac{\omega^2}{2}\Big|_{\omega_0}^{\omega_T} = -\frac{G}{J_z} \cdot sin(\alpha + \varphi)\Big|_0^{\pi/2};$$

$$\frac{\omega_T^2}{2}-\frac{\omega_0^2}{2}=-\frac{G}{Jz}\cdot sin(\alpha+\frac{\pi}{2})+\frac{G}{Jz}\cdot sin\,\alpha;\ sin\,\alpha=\frac{h}{\sqrt{h^2+\frac{b^2}{4}}}=\frac{2\cdot h}{\sqrt{4\cdot h^2+b^2}};\tag{17}$$

$$\omega_T=\sqrt{2\cdot\frac{G}{J_z}\cdot\left(\frac{2\cdot h}{\sqrt{4\cdot h^2+b^2}}-\frac{b}{\sqrt{4\cdot h^2+b^2}}\right)+\omega_0^2}$$

As a result, we get that with one flip of the object

$$\omega_T=\sqrt{2\cdot\frac{G}{J_z}\cdot\frac{1}{\sqrt{4\cdot h^2+b^2}}\cdot(2\cdot h-b)+\omega_0^2}\tag{18}$$

where ω – is the angular velocity; J – is the moment of inertia.

When the object is turned over more than one time (once)

$$V_{0\tau}=V\cdot\varepsilon;V=\omega\cdot R\tag{19}$$

where ε – is the recovery coefficient.

Thus, the proposed model allows to calculate all the parameters of interest to the expert to determine the mechanism of overturning the vehicle.

3 Conclusions

As a result of the research, a method has been developed for calculating the parameters of vehicle movement in case of loss of directional stability as a result of uncontrolled movement after collisions. The use of the proposed method allows a differentiated approach to the calculations of various situations associated with complex movement of vehicles as a result of their collision, as well as further expand the array of calculated parameters of movement of vehicles with participation in the event of a traffic accident through the introduction of additional initial data for calculation, for example, such as the position of wheels relative to the sliding plane during uncontrolled movement, their rotation or blocking with consideration of different force balance and its influence on the prediction of the movement under study.

It is also proposed a method for calculating the parameters of vehicle movement in case of loss of vertical stability as a result of one or more revolutions around horizontal axes. The proposed method makes it possible to calculate the parameters of moving vehicles before they lose vertical stability, taking into account the displayed array of trace information, which had not previously been proposed for use in the automotive literature.

These methods make it possible to more accurately investigate the mechanism of road accidents at the stage of discarding, which in turn can lead to a more complete understanding of the mechanism of the incident as a whole.

References

1. I.S. Brylev, *Reconstruction of road accidents according to the parameters of the braking process of two-wheeled motor vehicles: Diss. cand. teh. nauk* (SPbGASU, St. Petersburg, 2015)
2. A.A. Eichenwald, *Theoretical Physics: Solid State Mechanics* (PH Librokom, Moscow, 2011)

3. A.A. Eichenwald, *Theoretical Physics: General Mechanics* (PH Librokom, Moscow, 2016)
4. S.A. Evtiukov, Y.V. Vasiliev, *Investigation and examination of road traffic accidents* (DNA Publishing House LLC, St. Petersburg, 2005)
5. S.S. Evtiukov, *Assessment of the speed of vehicles during road traffic examinations: dissertation candidate Techne. Sciences* (SPb, 2014)
6. V.A. Kovalev et al, Determining the speed of possible aquaplaning. Bulletin of Irkutsk State Technical University **5(88)** (2014)
7. R.R. McHenry, *Development of a computer program to aid the investigation of highway accidents Tech.Rep.DOT/HS 800 621, Contact Number FH-11-7526* (Cornel Aeronautical Laboratory, Inc. (CALSPAN Corp.), 1971)
8. R.R. McHenry, *Mathematical Reconstruction of highway accidents. DOT HS 801-405, Calspan Report No. ZQ-5341-V-2* (Washington D.C., 1975)
9. V.N. Nikonov, *Finite element method and forensic engineering strength examination. - Materials of the All-Russian Scientific Practical Conference "Reconstruction of the Circumstances of a Traffic Accident during Forensic Examinations. Law and methodological issues of forensic examination"* (Ufa, 2008)
10. I. Novikov, A. Degtyar, D. Lazarev, V. Makhonin, MATEC Web of Conferences **341**, 00070 (2021) https://doi.org/10.1051/matecconf/202134100070.
11. I.A. Novikov, D.A. Lazarev, Transportation Research Procedia **20**, 463-467 (2017)
12. I.A. Novikov, D.A. Lazarev, D.V. Kudinov, International Journal of Applied Engineering Research **21**, 42721-42724 (2015)
13. E. Rous, *Rigid body dynamics. Tr. from English in 2 volumes V1* (PH Science, Moscow, 1983)
14. Y.B. Suvorov, *Forensic road traffic examination. Forensic assessment of the actions of drivers and other persons responsible for ensuring road safety in accident areas. Educational assistance for universities* (PH Examination, PH Law, Moscow, 2004)
15. S.M. Targ, *Short course in theoretical mechanics* (PH The higher school, Moscow, 2007)
16. M.G. Valishchev, A.A. Povzner, *General Physics Course* (PH Lan, Moscow, 2010)
17. A.A. Yablonsky, V.M. Nikiforova, *Course in theoretical mechanics. Educational assistance for universities* (PH Integral Press, Moscow, 2009)