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POSSIBILITIES FOR ASSESSING THE PRE-COLLISION AND POST-COLLISION VEHICLES SPEEDS, IN THE EVENT OF SIDE COLLISIONS, BY THE QUANTITY OF MOTION CONSERVATION LAW

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Abstract: *The paper evaluates, from a physical-mathematical point of view, the pre-collision and post-collision vehicles' speeds, in case of side collisions, by preserving the amount of movement, taking into account the parameters resulting from the primary investigation of the scene. By reconstructing such road traffic accidents, the aim is to determine the kinematic quantities that influence the behavior of the vehicles involved in the accident, and to allow the analysis of the possibilities to avoid the collision. It also takes into account the situation in which the vehicles perform, in addition to the translational movement, a rotational movement around the vertical axes that pass through their centers of gravity. The developed working algorithm allows to change the input data (it can be applied to solve a large number of road traffic accident cases) and to obtain the results necessary for the reconstruction of such accidents. Thus, it is possible to establish the dynamics of this type of road accidents, which facilitates the assessment and comparison of different conditions taken into consideration.*

Key words: *vehicle, road accident, amount of movement, numerical modeling*

1. INTRODUCTION

During a road traffic accident there are three phases [5, 6, 8, 9, 12, 13, 15]:

- pre-collision - a period before the accident, that takes place until the moment when the two bodies come into contact;
- the collision - corresponds to the period in which the two bodies are in contact; during this interval takes place the deformation of the body and other elements of the vehicles, a process by which a part of the initial kinetic energy is transformed into deformation energy;
- post-collision - takes place from the moment of detachment of the two bodies until their stopping; it should be noted that in some cases multiple collisions occur, i.e. a body comes into contact with other bodies several times (for example, after a frontal collision, a car hits a tree).

Many cases of road traffic accidents require the reconstruction of the consecutive stages of their development, in order to identify the causes that contributed to their occurrence, the influence of various factors involved (human-, vehicle- and road-related) and not in lastly, the identification of maneuvers that could be carried out in order to avoid them. In this context, the analysis of the dynamics of road traffic accidents is an important and very current activity [15].

The complexity of the reconstruction of a road traffic accident depends on the number and nature of the factors that influence it [15].

The understanding of a road traffic accident generally refers to [15]:

- establishing the parties involved;
- establishing the actual scene of the accident (geographical configuration, nature and condition of the running surface, existing traffic signs, etc.);
- severity of the accident.

All these are elements of investigation, which are recorded at the scene of the accident. In most cases, the first two elements are relatively easy to establish, being objective observations. Regarding the severity of the accident, the investigator understands the economic costs, while medical personnel understands the severity of injuries and traumas. The latter are unusable elements in the investigation of road traffic accidents, in almost all cases [15].

Once the road traffic accident has been understood, the investigators proceed to establish, test and then implement the measures in order to reduce the number of accidents. This is done by different methods, depending on the most common causes of road traffic accidents [15].

The use of calculation methods for the investigation of a road traffic accident is part of the understanding of the accident. During the investigation of a road traffic accident, it is evaluated, in the sense of its reconstruction, different kinematic or dynamic parameters of the parties involved. For this, it is necessary to extract the required input quantities from the existing samples, apply a calculation method and test the obtained results [7, 15].

The evolution over time of the kinematic quantities that characterize a road traffic accident, can be captured by using numerical calculation models [4, 7, 8, 10, 15, 18], developed in the sense of using as many variables as possible to be encountered in situations of a road event, and the obtained results can be presented synthetically in tabular or in graphic form.

2. NUMERICAL EVALUATION METHOD

To determine the pre-collision and post-collision vehicle speeds, in the case of the oblique collision of two vehicles of masses m_1 and m_2, which meet in an intersection (Fig. 1), in which the angle between the longitudinal axes of the vehicles is α_1 (angle of the two streets), and the angle between the normal collision axis of the vehicles (n - the direction on which the percussion P acts) and the axis of symmetry of the horizontal road is α_2, the initial velocities v_1 and v_2 of the vehicles are decomposed according to the direction of their common normal axis of the collision (subscript n), respectively after a direction perpendicular to it (subscript t) (Fig. 2) [12, 14, 15].

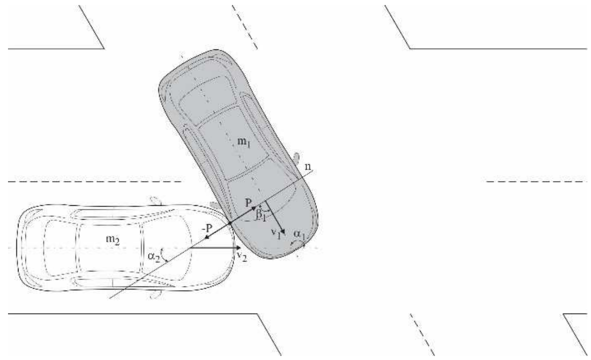

Fig. 1. Scheme of the side collision between two vehicles.

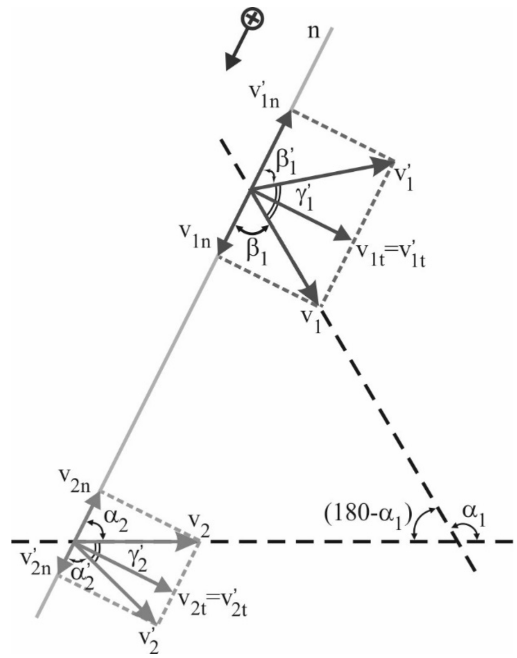

Fig. 2. Vehicle speeds in case of their oblique collision.

Since in the tangential direction we do not have active forces, it results that after the collision only the normal components of the velocities (v'_{1n} and v'_{2n}) will change, and the components v'_{1t} and v'_{2t} keep the same value as before the impact ($v'_{1t} = v_{1t}$, $v'_{2t} = v_{2t}$) [12, 14, 15]. The components of the velocities (see Fig. 2) are determined by considering an equivalent case of frontal collision, according to the direction of the common normal axis of the collision. In the present case, considering that in the post-collision phase the vehicles reject each other in the direction of the common normal of the collision (see Fig. 2), the normal components of velocities (v'_{1n} and v'_{2n}) will be given by the relations [12, 14, 15]:

$$\begin{cases} -v'_{1n} = v_{1n} - \frac{m_2}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k) \\ v'_{2n} = -v_{2n} + \frac{m_1}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k) \end{cases}. \quad (1)$$

According to the law of conservation of momentum, the energy of two bodies after the collision is equal to the sum of the kinetic energies before the collision, diminished by the deformation energy of the two bodies. The law applies to the translational motion and to the rotational motion.

For the translational movement on the normal direction of the two vehicles' collision, the variation of the momentum of each of the two vehicles, respectively their corresponding percussion (see Fig. 1, Fig. 2), $P = m_1 \cdot (v_{1n} + v'_{1n}) = m_2 \cdot (v_{2n} + v'_{2n})$, may be expressed in terms of normal components of pre-collision speeds (taking into account relations (1), $P = f(v_{1n}, v_{2n})$, thus [12, 15]:

$$P = \frac{m_1 \cdot m_2}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k). \quad (2)$$

In the post-collision phase, the vehicles also perform a rotational movement around the vertical axes that pass through their centers of gravity. Thus, moments of mass inertia $I_{1,2}$ appear around the axes passing through the centers of gravity of the two vehicles (in the direction of O_z) [12, 15]:

$$\begin{cases} I_1 \cdot \omega'_1 - I_1 \cdot \omega_1 = P \cdot B_1 \\ I_2 \cdot \omega'_2 - I_2 \cdot \omega_2 = P \cdot B_2 \end{cases}, \quad (3)$$

where: $\omega_{1,2}$ are the pre-collision angular velocities; $\omega'_{1,2}$ - post-collision angular velocities; $B_{1,2}$ - vehicle half-widths.

The moments of mass inertia $I_{1,2}$ are given by the relation [8, 12, 15]:

$$\begin{cases} I_1 = \frac{m_1 \cdot (L_1^2 + B_1^2)}{12} \\ I_2 = \frac{m_2 \cdot (L_2^2 + B_2^2)}{12} \end{cases}, \quad (4)$$

where: $L_{1,2}$ are the overall lengths of the vehicles.

In relations (3), the pre-collision angular speeds are neglected (this assumes that, before the impact, the vehicles move without skidding). Given this, from the relations (3) the post-collision angular velocities can be expressed as a function of the percussion P, as follows [12, 15]:

$$\begin{cases} \omega'_1 = \frac{P \cdot B_1}{I_1} \\ \omega'_2 = \frac{P \cdot B_2}{I_2} \end{cases}. \quad (5)$$

Thus, the post-collision angular velocities of motor vehicles can be expressed according to the pre-collision velocities [12, 15]:

$$\omega'_{1,2} = f(v_{1n}, v_{2n}). \quad (6)$$

Given that after impact, the vehicles also had translational and rotational motion, the mechanical work developed by each of the two vehicles after the collision is [12, 15]:

$$\begin{cases} L_{m_1} = L_{t_1} + L_{r_1} + L_{d_1} \\ L_{m_2} = L_{t_2} + L_{r_2} + L_{d_2} \end{cases}, \quad (7)$$

wherein: $L_{t_{1,2}}$ is the mechanical translation work for each of the two vehicles; $L_{r_{1,2}}$ - mechanical rotation work; $L_{d_{1,2}}$ - mechanical work corresponding to plastic deformations.

The mechanical work of translation is given by the relation [12, 15]:

$$\begin{cases} L_{t_1} = R_1 \cdot S_{opr_1} \\ L_{t_2} = R_2 \cdot S_{opr_2} \end{cases}, \quad (8)$$

wherein: $R_{1,2}$ is the displacement resistance force; $S_{opr\,1,2}$ - the distance traveled by the vehicles from the collision to the stopping.

The force of resistance to displacement can be expressed as follows [12, 15]:

– in case of dragged movement,

$$\begin{cases} R_1 = \varphi_1 \cdot m_1 \cdot g \\ R_2 = \varphi_2 \cdot m_2 \cdot g \end{cases}, \quad (9)$$

– in the case of free movement,

$$\begin{cases} R_1 = f_1 \cdot m_1 \cdot g \\ R_2 = f_2 \cdot m_2 \cdot g \end{cases}, \quad (10)$$

where: $\varphi_{1,2}$ is the grip coefficient, the values of which are chosen according to [8, 11, 12, 15, 16, 17] (if the road is longitudinally inclined, then will be considered that the coefficient $\varphi_{1,2_0} = \varphi_{1,2} \cdot \cos\alpha \pm \sin\alpha$, "+" ascent, "–" descent

[4, 12, 15]); $m_{1,2}$ - the vehicles' masses; g - gravitational acceleration; $f_{1,2}$ - the coefficient of rolling resistance, whose values are chosen according to [1, 8, 11, 12, 15, 16, 17] (if the road is with longitudinal slope, then the coefficient, $f_{1,2_0} = f_{1,2} \cdot \cos\alpha \pm \sin\alpha$ "+" will be considered ascent, "–" descent [4, 12, 15]).

The slope-angle correlation can be identified according to the following relation [1, 15]:

$$p\,[\%] = 100 \cdot \mathrm{tg}\alpha\,;\ \alpha = \mathrm{arctg}\left(\frac{p\,[\%]}{100}\right).$$

The mechanical work of rotation is given by the relation [12, 15]:

$$\begin{cases} L_{r_1} = \frac{\varphi_y \cdot G_{a_1} \cdot \theta_1 \cdot \pi}{180 \cdot A_1} \cdot \left[b_1 \cdot \sqrt{\left(\frac{B_1'}{2}\right)^2 + a_1^2} + a_1 \cdot \sqrt{\left(\frac{B_1''}{2}\right)^2 + b_1^2}\right] \\ L_{r_2} = \frac{\varphi_y \cdot G_{a_2} \cdot \theta_2 \cdot \pi}{180 \cdot A_2} \cdot \left[b_2 \cdot \sqrt{\left(\frac{B_2'}{2}\right)^2 + a_2^2} + a_2 \cdot \sqrt{\left(\frac{B_2''}{2}\right)^2 + b_2^2}\right] \end{cases}, \tag{11}$$

where: $\theta_{1,2}$ are the angles at which the two vehicles rotate in the plane of the road, in degrees, $\left(\frac{\theta_{1,2} \cdot \pi}{180} \to \mathrm{rad}\right)$; $G_{a_{1,2}}$ - total weights of vehicles; $A_{1,2}$ - wheelbase of vehicles; $a_{1,2}$ - distance from the center of gravity to the front axle of the vehicle 1 and 2, respectively (determined as a function of wheelbase, according to [1, 11, 12, 15, 17, 18]); $b_{1,2}$ - distance from the center of gravity to the rear axle of the vehicle 1, and 2, repectively; $B_{1,2}'$ - wheelbase of the front axle, for the two vehicles; $B_{1,2}''$ - rear axle wheelbase for vehicle 1 and 2, respectively; φ_y - lateral (transverse) grip coefficient, ($\varphi_y \cong 0{,}8 \cdot \varphi$).

The mechanical work corresponding to the plastic deformations, for the first and the second vehicle, can be expressed with the help of the relation [12, 15]:

$$\begin{cases} L_{d_1} = \frac{\sigma_{c_1}^2}{E_1} \cdot \frac{m_1'}{\rho_1} \\ L_{d_2} = \frac{\sigma_{c_2}^2}{E_2} \cdot \frac{m_2'}{\rho_2} \end{cases}, \tag{12}$$

wherein: $\sigma_{c_{1,2}}$ is the yield strength of the deformed material, in N/m^2, (for body elements: 180...340 MPa - made of steel, 110...130 MPa - made of aluminum alloys; for load-bearing structure: 250...500 MPa); $m_{1,2}'$ - plastically deformed mass, in kg; $E_{1,2}$ - longitudinal modulus of elasticity (Young's modulus), in N/m^2, (approx. $2.1 \cdot 10^5$ MPa - for steel; approx. $0.7 \cdot 10^5$ MPa - for aluminum alloys); $\rho_{1,2}$ - density of the deformed material, in kg/m^3, (approx. $7.8 \cdot 10^3$ kg/m^3 - for steel; approx. $2.7 \cdot 10^3$ kg /m^3 - for aluminum alloys) [2, 3, 12, 15].

After the impact, the relations (kinetic energies after the impact) can be used [12, 15]:

$$\begin{cases} E_{c_{t_1}} = E_{c_{tr_1}} + E_{c_{rot_1}} \\ E_{c_{t_2}} = E_{c_{tr_2}} + E_{c_{rot_2}} \end{cases}, \tag{13}$$

where: $E_{c_{tr}}$ is the kinetic energy of translation, given by the relation [12, 15]:

$$\begin{cases} E_{c_{tr_1}} = \frac{m_1 \cdot (v_{1n}')^2}{2} \\ E_{c_{tr_2}} = \frac{m_2 \cdot (v_{2n}')^2}{2} \end{cases}, \tag{14}$$

and $E_{c_{rot}}$ is the kinetic energy of rotation, given by the relation [7, 10, 12, 15]:

$$\begin{cases} E_{c_{rot_1}} = \frac{I_1 \cdot (\omega_1')^2}{2} \\ E_{c_{rot_2}} = \frac{I_2 \cdot (\omega_2')^2}{2} \end{cases}. \tag{15}$$

Given that the kinetic energy of a body measures the mechanical work accumulated by that body in the form of motion due to the action of the external forces, then it can be written [12, 15]:

$$\begin{cases} E_{c_{t_1}} = L_{m_1} \\ E_{c_{t_2}} = L_{m_2} \end{cases}, \tag{16}$$

resulting [12, 15]:

$$\begin{cases} I_1 \cdot (\omega_1')^2 + m_1 \cdot (v_{1n}')^2 = 2 \cdot L_{m_1} \\ I_2 \cdot (\omega_2')^2 + m_2 \cdot (v_{2n}')^2 = 2 \cdot L_{m_2} \end{cases}. \tag{17}$$

The normal components of the post-collision velocities (v'_{1n} and v'_{2n}) are expressed as a function of the normal components of the pre-collision velocities (v_{1n} and v_{2n}) (see relation 1), and the post-collision angular velocities $\omega'_{1,2}$ are expressed as a function of v_{1n} and v_{2n}. With the help of relation (6), they can be replaced in relations (17), together with relations (4) and (7), resulting in a system of two quadratic equations, having as unknown the normal components of the pre-collision velocities (v_{1n} and v_{2n}), as follows [12, 15]:

$$\begin{cases} I_1 \cdot \left[\frac{m_1 \cdot m_2}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k) \cdot \frac{B_1}{I_1}\right]^2 + m_1 \cdot \left[-v_{1n} + \frac{m_2}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k)\right]^2 = 2 \cdot L_{m_1} \\ I_2 \cdot \left[\frac{m_1 \cdot m_2}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k) \cdot \frac{B_2}{I_2}\right]^2 + m_2 \cdot \left[-v_{2n} + \frac{m_1}{m_1+m_2} \cdot (v_{1n} + v_{2n}) \cdot (1+k)\right]^2 = 2 \cdot L_{m_2} \end{cases} . \quad (18)$$

After determining the normal components of the pre-collision velocities (v_{1n} and v_{2n}), the normal components of the post-collision velocities (v'_{1n} și v'_{2n}) can be calculated (see relation 1) and, taking into account the geometry of the accident site (see Fig. 1 and 2) both the pre-collision speeds (v_1 and v_2) and the post-collision speeds (v'_1 și v'_2) of the vehicles can be determined as follows:

$$\begin{cases} v_1 = \frac{v_{1n}}{\cos\beta_1} \\ v_2 = \frac{v_{2n}}{\cos\alpha_2} \end{cases}, \quad (19)$$

$$\begin{cases} v'_{1t} = v_{1t} = v_1 \cdot \sin\beta_1 \\ v'_{2t} = v_{2t} = v_2 \cdot \sin\alpha_2 \end{cases}, \quad (20)$$

$$\begin{cases} v'_1 = \sqrt{(v'_{1n})^2 + (v'_{1t})^2} \\ v'_2 = \sqrt{(v'_{2n})^2 + (v'_{2t})^2} \end{cases}, \quad (21)$$

where $\beta_1 = (\alpha_1 - \alpha_2)$ (see Fig. 2).

The directions and positions of the velocity vectors, after the collision, can be determined using the relations:

$$\begin{cases} \beta'_1 = \operatorname{arctg}\left(\frac{v'_{1t}}{v'_{1n}}\right) \\ \alpha'_2 = \operatorname{arctg}\left(\frac{v'_{2t}}{v'_{2n}}\right) \end{cases}, \quad (22)$$

$$\begin{cases} \gamma'_1 = 180 - (\beta_1 + \beta'_1) \\ \gamma'_2 = 180 - (\alpha_2 + \alpha'_2) \end{cases}. \quad (23)$$

3. OBTAINED RESULTS

For example, in the numerical calculation model, developed in the MathCAD program, is sought the determination of the pre-collision and post-collision velocities, taking into account the input data captured in table 1.

Depending on the case of the collision, in the normal direction of collision will be considered a frontal collision with different post-collision behavior of vehicles involved in the road event, which, in addition to the translational motion, also have a rotational motion around the vertical axes passing through their centers of their weight, the development of the calculation algorithm is followed, so that, by changing the input data, the numerical model can be adapted to any other situation of lateral impact, front-rear or front, with different post-collision behavior and allowing to obtain results related to the pre-collision and post-collision vehicles' speeds.

Taking into account the working diagram in Figure 3 and the input data in Table 1, the numerical calculation model developed allows the determination of pre-collision and post-collision vehicles' speeds involved in the accident, the results can be obtained tabular (see Table 1) or graphically.

4. CONCLUSIONS

Considering the data resulting from the report of a road traffic accident, identifying the case of collision and behavior of the vehicles involved, by entering them in the appropriate calculation algorithm, the desired results can be obtained automatically.

By developing such numerical models for the reconstruction of road-vehicle accidents, in the case of side impact, it ca be concluded:

- the analytical models offer the possibility to reconstruct the road traffic accidents and the numerical and graphic simulation of these accidents, respectively;

- one of the advantages of physical and mathematical modeling is that, knowing the position of traffic participants, one can determine the pre-collision and post-collision speeds of vehicles, as well as their trajectory;
- the developed working algorithm allows the variation of input data and the obtaining of tabular or graphical results for any other impact situation of the vehicles, which facilitates the appreciation and comparison of the different studied conditions;
- the developed numerical model allows the reconstruction of road traffic accidents, for situations in which vehicles perform, in addition to the translational movement, a rotational movement around the vertical axes that pass through their centers of gravity, by applying the law of conservation of momentum;
- also, the developed method can be extended for the situations in which an energy balance can be made between the pre-collision phase and the post-collision phase during a road traffic accident.

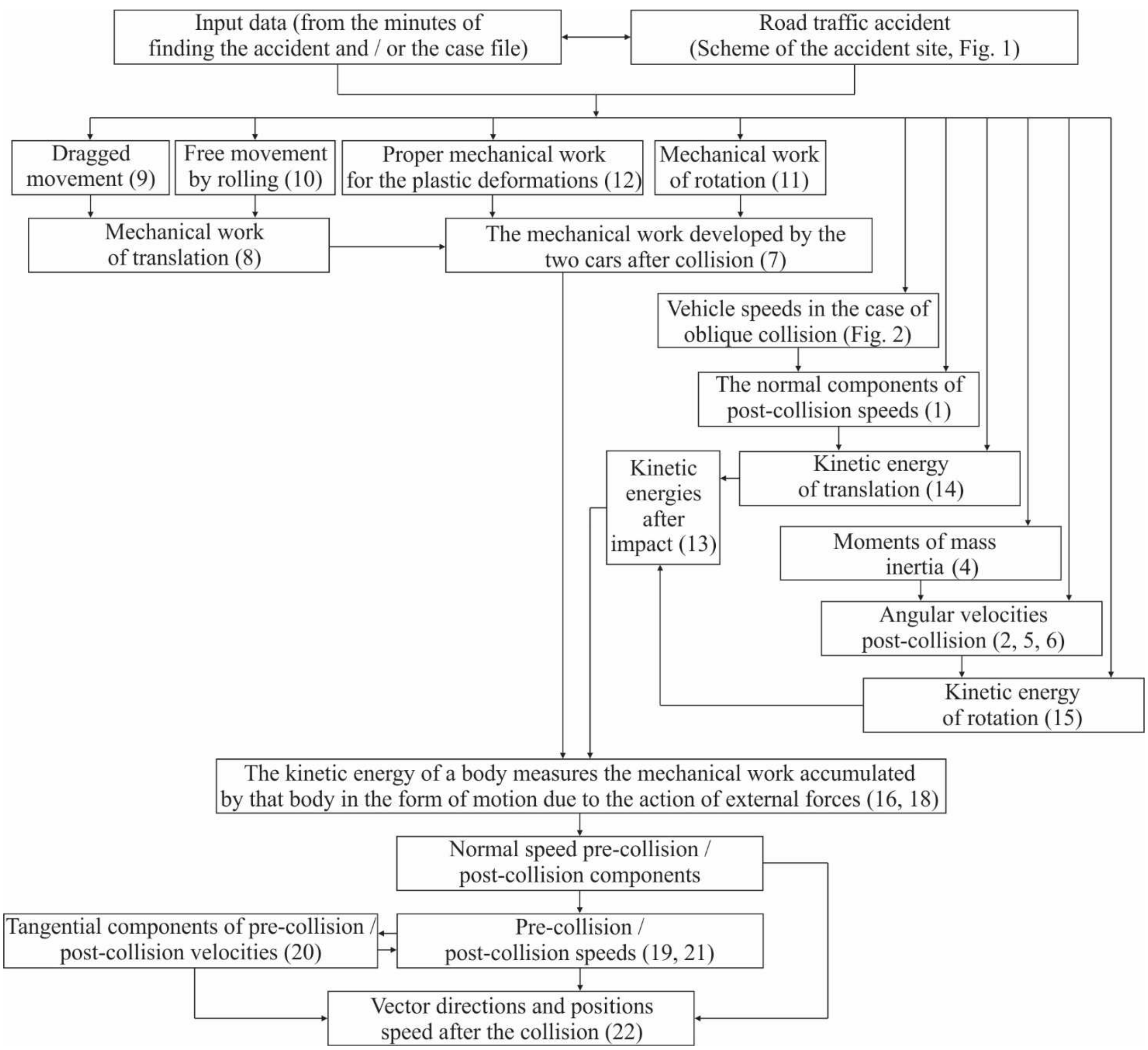

Fig. 3. Schedule for determining pre-collision / post-collision speeds, by the quantity of motion conservation law.

Table 1

Input data and the obtained results

Type size	Parameter	Notation	Vehicle 1	Vehicle 2	Unit of measurement
Initial sizes	❑ the masses of the vehicles	$m_{1,2}$	1680	1620	kg
	❑ the wheelbase of the vehicles	$A_{1,2}$	2.665	2.765	m
	❑ front axle wheelbase	$B'_{1,2}$	1.437	1.513	m
	❑ rear axle wheelbase	$B''_{1,2}$	1.418	1.494	m
	❑ the overall lengths of the vehicles	$L_{1,2}$	4.248	4.448	m
	❑ the widths of the vehicles	$B_{1,2}$	0.845	0.868	m
	❑ the distance traveled from the collision to the stopping	$S_{opr_{1,2}}$	20	21	m
	❑ the angles at which the vehicles rotate	$\theta_{1,2}$	110	160	°
	❑ plastically deformed masses	$m_{1,2}$	110	120	kg
	❑ the angle between the longitudinal axes of the vehicles (the angle of the two streets)	α_1	110		°
	❑ angle between the normal collision axis of the vehicles and the symmetry axis of the horizontal road	α_2	70		°
	❑ grip coefficient	φ	0.75		-
	❑ gravitational acceleration	g	9.81		m/s^2
	❑ flow limit of the deformed material	σ_c	$150 \cdot 10^6$		N/m^2
	❑ longitudinal modulus of elasticity	E	$2.1 \cdot 10^{11}$		N/m^2
	❑ density of the deformed material	ρ	$7.8 \cdot 10^3$		kg/m^3
	❑ coefficient of restitution	k	0.3		-
Calculated sizes	❑ normal components of pre-collision velocities	$v_{1n,2n}$	32.991	21.134	km/h
	❑ the initial velocities of the vehicles	$v_{1,2}$	43.067	61.792	km/h
	❑ tangential components of pre-collision / post-collision velocities	$v_{1t,2t}; v'_{1t,2t}$	27.683	58.065	km/h
	❑ normal components of post-collision velocities	$v'_{1n,2n}$	1.551	14.687	km/h
	❑ post-collision vehicles' velocities	$v'_{1,2}$	27.726	59.894	km/h
	❑ the directions of the velocity vectors, after the collision, compared to the normal collision direction	β'_1, α'_2	86.794	75.805	°
	❑ the directions of the velocity vectors, after the collision, with respect to the initial velocity	$\gamma'_{1,2}$	53.206	34.195	°

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POSIBILITĂȚI DE EVALUARE A VITEZELOR ANTECOLIZIUNE ȘI POSTCOLIZIUNE ALE AUTOVEHICULELOR, ÎN CAZUL COLIZIUNILOR LATERALE, PRIN LEGEA CONSERVĂRII CANTITĂȚII DE MIȘCARE

Rezumat: În lucrare se evaluează, din punct de vedere fizico-matematic, vitezele antecoliziune și postcoliziune ale autovehiculelor, în cazul coliziunilor laterale, prin conservarea cantității de mişcare, ţinând seama de parametrii rezultați din cercetarea primară a locului faptei. Prin reconstituirea unor asemenea accidente rutiere se urmărește determinarea mărimilor cinematice care influențează comportamentul autovehiculelor implicate în accident, și care să permită analiza posibilitățile de evitare a accidentului. Se ţine seama și de situațiile în care autovehiculele realizează pe lângă mişcarea de translaţie şi o mişcare de rotaţie în jurul axelor verticale care trec prin centrele lor de greutate. Algoritmul de lucru dezvoltat permite schimbarea datelor de intrare (poate fi aplicat la soluționarea unui număr mare de cazuri de accidente rutiere) și obținerea rezultatelor necesare reconstituirii unor asemenea accidente rutiere. Astfel, este posibilă stabilirea dinamicii producerii accidentelor rutiere de acest tip, ceea ce facilitează aprecierea şi compararea diferitelor condiții luate în studiu.

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