Upon the reconstruction of accidents triggered by tire explosion. Analytical model and case study

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Abstract. Accident Reconstruction is important in the general context of increasing road traffic safety. In the casuistry of traffic accidents, those caused by tire explosions are critical under the severity of consequences, because they are usually happening at high speeds. Consequently, the knowledge of the running speed of the vehicle involved at the time of the tire explosion is essential to elucidate the circumstances of the accident. The paper presents an analytical model for the kinematics of a vehicle which, after the explosion of one of its tires, begins to skid, overturns and rolls. The model consists of two concurent approaches built as applications of the momentum conservation and energy conservation principles, and allows determination of the initial speed of the vehicle involved, by running backwards the sequences of the road event. The authors also aimed to both validate the two distinct analytical approaches by calibrating the calculation algorithms on a case study

1. Introduction

Overturning and rolling a vehicle involves a high enough energy input; it is taken from the kinetic energy, which means that such accidents occur at relatively high speeds. Overturning accidents have the specificity that the vehicle can no longer be controlled, it's movement being made by sliding and rolling the body. For these reasons, the consequences of these accidents are generally serious, both for the occupants of the overturned car and for the other road users.

Generally, the overturning of the vehicle has a unique cause, namely the action of a mechanical momentum generated by lateral forces whose arm is related to the road contact points of the wheels that remain in contact with the tread. The lateral forces that generate the overturning moment are the result of either the driver - road interaction or the defects that occurred during the vehicle's travel. In the second case, the most common accidents are generated by the explosion of a tire, as a consequence of dynamic imbalances generated in vehicle's movement. Sometimes, after the explosion, the evolution of the vehicle can also be marked by the driver's behaviour if he performs braking maneuvers and/or tight turns. The cause of such a roll is relatively easy to set up after the typical trace on the road as well as damage analysis after the accident.

In the study and analysis of road accidents is particularly important to establish kinematics parameters during events (vehicle speed in the main stages of movement of motor vehicles and victims, distances traveled by the vehicle during these stages) and kinematic parameters that would allow to avoid the event (the speed of the vehicle for the event could have been avoided).

Over the years there have been developed various models for calculating the vehicles speeds at different stages of an accident, patterns that differ depending on the type of event to which it is addressed (energetic brakes, collisions, pedestrian hits, etc.), the theoretical principles applied in establishing relationships calculation, the possibility of using traces aquired at the scene. Thus, an accident reconstruction will require a decision on the appropriate calculation model, and adapt it to the specific case of the respective accident.

The paper presents an analytical model for determining the initial velocity of a vehicle involved in an accident triggered by the explosion of one of its tires. Further movement of the vehicle was in the first phase of skidding, then overturning and rolling. The elaborated model was calibrated in the paper, being applied on a case study.

2. The determination of the speed of the vehicle at the moment of the accident

Between the moments of the tire explosion and the overturning, the vehicle is skidding. The determination of the vehicle's speed before skidding is based on an energy method, constituting in fact an adaptation of the energy conservation law applied between the initial and final moments of the skid phase.

The speed of the vehicle before skidding, w_0 [m/s], is determined with the equation:

$$w_0 = \sqrt{w_i^2 + 2 \cdot \varphi_t \cdot g \cdot S_d} \quad (1)$$

where: w_i [m/s] – vehicle speed at the end of skidding phase; φ_t [-] - transverse adhesion coefficient; g=9.81 [m/s^2] - gravitational acceleration; S_d [m] - skidding distance.

S_d is determined by measurements at the site of the accident taking into consideration the specific methodology for investigating and assessing skidding traces.

The approach of the skidding direction by considering the anisotropy of the adhesion coefficient in the contact surface between the tire and the track is original and is justified by the need to increase the precision of the speed determination. Alternatively, an experimentally determined resistance coefficient can be used, but it does not reflect the influence of skidding direction.

Adherence on the transverse direction is less than on the longitudinal direction, due to the fact that the forms and surfaces of contact spots are different when sliding friction occurs on the longitudinal or transverse direction, due to the tires construction. As a result, the transverse adhesion coefficient [1] will be determined with the equation:

$$\varphi_t = 0.8 \cdot \varphi \quad (2)$$

with φ [-] – longitudinal adhesion coefficient, which is expressed according to the road structure, road condition and tire type.

2.1. Determining the speed of the vehicle at the start of rolling phase

A first approach for determining the speed of the vehicle at the start of rollover is based on the law of impulse conservation. Special attention should be given to identifying the axle of the vehicle after which the vehicle is rolled.

In principle, the lateral movement component, produced by skidding combined with the initial longitudinal translation motion of the vehicle, determines its complex, parallel planar evolution in the road surface. Frequently, due to this complex motion, the rollover is initiated around an axis containing the contact points of the wheels of the same axle with the rolling path.

The accurate setting of the axis after which the overturning is initiated will be based on the acquisition and interpretation of the vehicle's traces and from the scene of the accident. Our model considers that rollover occurs around the transverse axis that contains the contact points of the front wheels of the vehicle with the road.

Generally, in the vehicle's lifting movement in neutral stability position (NSP), the mechanical rotating work of the vehicle around the above-mentioned axis is entirely transformed into the potential energy of the vehicle at the NSP.

Therefore, the vehicle energy when the rollover starts is given by:

$$\frac{J_{ty}\cdot\omega^2}{2} = M\cdot g\cdot\left[\sqrt{\left(\frac{A}{2}\right)^2 + h^2} - h\right] \tag{3}$$

where J_{ty} [kg·m^2] represents the mass moment of inertia of the vehicle relative to a transverse axis passing through the contact points between the road and the front wheels; ω[rad/s] - the angular velocity of the vehicle in relation to this axis; h[m] - the vehicle's center of gravity height; M[kg] - total weight of the vehicle (including the curb weight and mass of passengers); A[m] – the vehicle wheelbase.

For passenger vehicles the height h is determined, according to [1], from:

$$\frac{h}{A} = 0.195 \ldots 0.23 \tag{4}$$

higher values characterizing loaded vehicle.

The mass moment of inertia J_{ty} is determined using Steiner's theorem:

$$J_{ty} = J_{yy} + M\cdot\left[\left(\frac{A}{2}\right)^2 + h^2\right] \tag{5}$$

where J_{yy} [kg·m^2] represents the mass moment of inertia of the vehicle relative to the transverse axis passing through its center of mass.

The mass moment of inertia J_{yy} is determined, according to [2], with the relation:

$$J_{yy} = \frac{H+h}{k_v}\cdot A\cdot M \tag{6}$$

H [m] – the height of the vehicle; k_v [-] – a coefficient that takes into account vehicle class and axis after which is calculated the mass moment of inertia [2].

From equation (3) is determined the angular velocity ω [rad/s] of the vehicle relative to this axis:

$$\omega = \sqrt{2\cdot M\cdot g\cdot\left[\sqrt{\left(\frac{A}{2}\right)^2 + h^2} - h\right]/J_{ty}} \tag{7}$$

Without taking into account the vehicle's deformations, speed w_i^* [m/s] at the beginning of rollover results from the equation of momentum conservation:

$$J_{ty}\cdot\omega = M\cdot w_i^*\cdot h \tag{8}$$

$$w_i^* = J_{ty}\cdot\omega/(M\cdot h) \tag{9}$$

The speed w_i [m/s] at the end of slippage phase is determined by the known relation:

$$w_i = \sqrt{w_i^{*2} + \frac{2\cdot E_d}{M}} \tag{10}$$

where E_d [J] - the deformation energy of the vehicle body elements.

For front or rear collision it has been defined a deformation coefficient C [2], [3], established experimentally, with the same dimensions [kN/m] as the elasticity coefficient.

If is denoted by $F(\zeta)$the function of force variation that produces deformation then we can write:

$$E_d = \int F(\zeta)\, d\zeta \;= \int C\cdot\zeta\, d\zeta \tag{11}$$

After integration, the deformation energy E_d of the vehicle is obtained by:

$$E_d = \frac{C_f}{2}\cdot\zeta_f^2 + \frac{C_s}{2}\cdot\zeta_s^2 \tag{12}$$

C_f [kN/m] – front stiffness coefficient; C_s [kN/m] – rear stiffness coefficient; ζ_f and ζ_S – medium deformations for the body vehicle at the front and rear part.

The structure of the vehicle and the deformations (depending on speed impact) have the greatest influences on the stiffness coefficients. Higher values for the C coefficients are characteristic for

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domains of low deformations or rear collisions. It has therefore been considered that the rollover described above produces deformation of the front and rear parts of the vehicle, similar to collinear collisions, both front and rear.

A second approach to the problem is purely energetic, considering the total dissipation of the kinetic energy of the vehicle from the initial moment of rolling, due to the rolling resistance of the vehicle. After t_{r0} [s], the vehicle will stop permanently from rolling after covering the distance S_r [m].

Thus, the w_i speed can be established also from the energy balance:

$$w_i = \sqrt{2 \cdot g \cdot f \cdot S_r} \tag{13}$$

Finally, one can determine the speed of the vehicle before slippage, w_0 from equation (1).
The time t_{r0} [s] in which was covered the distance S_r that the vehicle was rolling is determined based on the coefficient of running resistance, f:

$$t_{r0} = \frac{w_i}{f \cdot g} \tag{14}$$

Between the total angle of rotation θ (the angle of rotation of the vehicle during S_r) and angular velocity from the beginning of rotation exists the dependence:

$$\theta = \frac{2 \cdot \omega_r \cdot t_{r0}}{3} \tag{15}$$

where ω_r represents real angular velocity that must be entered in the momentum conservation equation:

$$\omega_r = \frac{M \cdot w_i \cdot h}{J_{ty}} \tag{16}$$

Since one rotation is the rotation of the car 360 degrees, finally is determined the total number of revolutions N, which is compared with data available from research at the accident site, checking the good agreement between reality and calculation methods :

$$N = \theta / 360° \tag{17}$$

We specify that the conditions of the road separation of the rear axle wheels and reaching the neutral stability position are assured implicitly due to the equation (3).

The algorithm neglects the energy consumed by the car to rotate 90 degrees during the skid, around the vertical axis (z - z) through its center of gravity, and the energy consumption of the suspension elements during the rollover phase. At the usual speeds of rollover accidents, these energy consumptions are really small and therefore negligible, and will slightly affect the precision of the calculation [4].

3. Model calibration. Case study

It was considered a real event, produced in Iasi County, an accident triggered by the explosion of the right rear tire of the vehicle. Further movement of the vehicle was in the first phase of skidding, then rolling.

The involved vehicle, Opel Vectra brand, has the following technical characteristics: wheelbase A = 2.64 [m]; Front track E = 1.435 [m]; Length L = 4.477 [m]; Width B = 1.707 [m]; Height H = 1.428 [m]; Own mass Mp = 1317 [kg].

At the time of the accident in the car there were 5 people, with a medium mass of 75 [kg], so the total mass of the car was: M = 1317 + 5 · 75 = 1692 [kg].

According to the investigation at the site of the accident, and the traces collected (figure 1), the car rolled around the transverse axis passing through its center of mass, the rolling being produced due to the tipping around the front wheels when they entered the rainwater drainage duct and they impacted in a tilted position the channel edge with the front side.

During the rolling, only the front and rear parts of the vehicle were in contact with the ground outside the road, blows that generated their intense deformation (the rear of the car was deformed inwards by a length ζ_s= 0.3 [m] and the front part was pushed inwards for a length ζ_f = 0.5 [m]) - figure 2.

Figure 1 – traces collected at the site of the accident

Between the traces printed on the road a distance of 1.6 [m] was measured. Considering the thickness of at least 0.2 [m] of a trace (at least equal to the width of the tread of a tire), it was determined the real distance between the middle of the traces: 1.6 + 0.2 = 1.8 [m], which is much larger than the front track E = 1.4 [m] of the car. It results with certainty that those traces are typical of skidding and not braking.

Figure 2 – the vehicle's front and rear part deformations

The slippage took place on a dry asphalt road with medium wear; in this case the longitudinal adhesion coefficient has a value φ = 0.65...0.7, given that this car was not equipped with ABS, and the transverse adhesion coefficient $\varphi_t = 0.8 \cdot \varphi = 0.8 \cdot (0.65...0.7) = 0.52...0.56$ [2]. From the moment when it began to print traces of skidding and until leaving with the front wheels the rainwater collecting channel, the car has traveled, according to the data acquired at the scene, a distance S_d = 38. 5 [m].

The rollover of a vehicle is carried out with a uniform deceleration. In such situations, the literature [5] recommends a coefficient of forward resistance f = 0.43 for rolling on the ground. According to the data acquired at the scene, and the accompanying sketch, the car rolled over a distance S_r = 36 [m]. For the analyzed car, the front stiffness coefficient C_f has a value of approx. 628 [kN/m] and the stiffness coefficient of the rear part is C_s = 467 [kN/m].

Applying the calculation algorithm described in the first part of the paper, it was determined the speed of the car before skidding, between 92.83 and 97 [km/h]. The total number of rotations N calculated was 1.45. In order for the car to stop on the roof (figure 3), 1.5 turns were needed and the calculated number is close to 1.5, with an error of only 3.3 [%], which reflects the good concordance between reality and calculation methodology.

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Figure 3 – the final position of the car, after the rollover

4. Conclusions

The paper presents a method of precise determination for the kinematic parameters of a vehicle which, as a result of the explosion of a tire, begins to skid, overturns and rolls, as well as the determination of rolls, made by the car till stop.

A limitation of this method is classic in the reconstruction of accidents and refers to the dependence of the method's precision by the abundance and the quality of traces acquired at the site of the accident. The method has limited applicability in the case of a vehicle that is overturned around a longitudinal axis. In this case, the deformations are placed on the lateral sides, the experimental data regarding the lateral stiffness coefficients of the vehicle being very poor. Last but not least, the overall precision of the model lies in the precision of determining the average deformations of the vehicle.

The originality of the paper is the simple but unitary approach of the analytical determination of the vehicle kinematics in accidents caused by tire explosions. The paper is representative from the aspect of considering the skidding direction and, implicitly, of the adhesion anisotropy, and also the correct identification of the axle around which the vehicle initiates the supposed rotation.

By applying the analytical model proposed in the paper it is possible to determine with sufficient precision the initial speed of a vehicle involved in a road accident triggered by the explosion of a tire, the vehicle subsequently evolving through skidding and overturning / rolling.

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