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EVALUATION OF THE INFLUENCE OF TRANSVERSE TRACK INCLINATION ON VEHICLE STABILITY PARAMETERS AT THE LIMIT OF SIDE ROLLOVER

Irina DUMA, Nicolae BURNETE, Adrian TODORUŢ, Nicolae CORDOŞ, István BARABÁS, Andreia MOLEA, Marian-Daniel DRAGOSTE, Radu-Mihai EFRIM, Alexandru TEREC

Abstract: *In this paper, the transverse stability parameters of vehicles in rollover are assessed from a physico-mathematical perspective, with a focus on their Static Stability Factor, considering the influence of the transverse slope of the road and the potential attainment of the Neutral Stability Position. Additionally, the travel speeds of vehicles are evaluated, at which skidding or lateral tipping may not occur but could be initiated. The working algorithm has been developed taking into account the forces acting on the vehicle during a turn, the position of the vehicle's center of gravity, its mass, the transverse inclination of the road, the vehicle's turning radius, and its dimensional and mass parameters.*
Key words: *Road vehicle, transverse stability, physico-matematical modelling, rollover*

1. INTRODUCTION

Various studies [1-22] on the stability of vehicles highlight the concerns of specialists in the field of vehicle dynamics and the dynamics of road traffic accidents. The results obtained through numerical calculations, computerized simulation, or experiments confirm several hypotheses and contribute to the ongoing development of the road traffic safety from this perspective.

In the case of the transverse stability of the vehicle, through the effect of lateral grip, its travel speed is directly influenced by the vehicle’s turning radius [16]. In the same context of transverse stability, in the situation of a transversal profile with a single slope or with two flat slopes, the vehicle’s critical speed is influenced both by the turning radius of the route traveled and by the road’s transverse inclination angle [16]. The maximum possible road turning radius increases with the increase in the vehicle's speed, but also with the decrease in the transverse slope angle of the road [16]. In the case of positive camber, the limit speed for cornering skid of the vehicle increases with the increase in the transverse slope angle of the road, while in the case of negative camber, it decreases with the increase in the transverse slope angle of the road [16].

To maintain the transverse stability of the vehicle, its travel speed must be adjusted based on the transverse slope of the road and its category, the turning radius of the path, as well as the vehicle’s dimensional and weight parameters [16].

In [10], it is presented a study on tire characteristics and their influence on the lateral stability of the vehicle, as well as on the possibilities of rollover occurrence. Parameters such as tire stiffness and slip angle are investigated to assess their influence on the maneuverability of the vehicle, aiming to explore how tire construction can be improved to reduce the risk of accidents caused by vehicle rollovers.

In [22], the influence of road geometry on the lateral stability of vehicles is investigated using a mathematical model. The impact of different road geometries, characterized by curvature

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radius and road profile irregularities, on the maneuverability and safety of the vehicle is analyzed. The study provides insights into possibilities for improving road design to reduce the risk of accidents caused by lateral instability of vehicles.

An alternative method for assessing transverse stability is presented in [2], where the combined effects of various vehicle parameters on static stability are considered. This includes tire characteristics, suspension parameters, and the position of the center of gravity. The study provides insights into enhancing vehicle design and improving safety through a more precise assessment of static stability.

Last but not least, the paper [1] aims to assess the influence of the curvature radius and transverse slope of the road on vehicle safety using a mathematical model. The authors analyze the impact of different curvature radii and lateral road slopes on the maneuverability and stability of the vehicle, focusing on identifying possibilities to reduce the risk of accidents caused by insufficient lateral stability. The study provides insights into improving road design and, consequently, safety during turns.

In this present study, the transverse stability parameters of vehicles in rollover are evaluated from a physico-mathematical perspective, primarily focusing on the assessment of the Static Stability Factor and the possibility of reaching the Neutral Stability Position. Thus, there is a continuation of the studies undertaken in [19], with the added consideration of the influence of the transverse slope of the road. In [19], there was a resort to the reconstruction of road accidents involving vehicle rollovers, in a scenario without transverse slope of the road.

The working algorithm has been developed to allow for the modification of input data and the generation of results with graphical interpretation.

2. ASSESSMENT OF STATIC STABILITY FACTOR AND LIMIT SPEEDS OF SLIDING AND ROLLOVER

In the case where the transverse inclination of the road is considered ($\beta > 0$), from the equation of momentum at the rollover point S (Fig. 1) [3, 4, 7, 8, 12-14, 16-21], by the condition of maintaining transverse stability at the limit rollover (normal road reaction on the right side wheels, $Z_d = 0$), the Static Stability Factor (SSF) is obtained for the rigid suspension variant, according to the relations [8, 19]:

$$\mathrm{SSF_{rs}} = \frac{a_y}{g} = \frac{\frac{E}{2 \cdot h_g} + \mathrm{tg}\,\beta}{1 - \frac{E}{2 \cdot h_g} \cdot \mathrm{tg}\,\beta}, \quad (1)$$

and, taking into account the expression for the transverse inertia force F_{iy}, $F_{iy} = G_a \cdot v_a^2/(g \cdot R)$ [4, 5, 14, 15, 17], the limit speed v_{ars_r} is obtained for the movement of the vehicle in a cornering, on a road with transverse inclination, where rollover does not occur but lateral rollover can begin, given by the relation [7, 12, 13, 15-18, 20, 21]:

$$v_{ars_r} = \sqrt{g \cdot R \cdot \frac{\frac{E}{2 \cdot h_g} + \mathrm{tg}\beta}{1 - \frac{E}{2 \cdot h_g} \cdot \mathrm{tg}\beta}}, \ \mathrm{[m/s]}, \quad (2)$$

where: g is the gravitational acceleration, in m/s²; R - the radius of the vehicle's path, in m; E - the vehicle's track width, in m; h_g - the height of the vehicle's center of gravity, in m; β - the transverse inclination angle of the road, in °; a_y - the vehicle's acceleration in the direction of the velocity vector (lateral acceleration), in m/s².

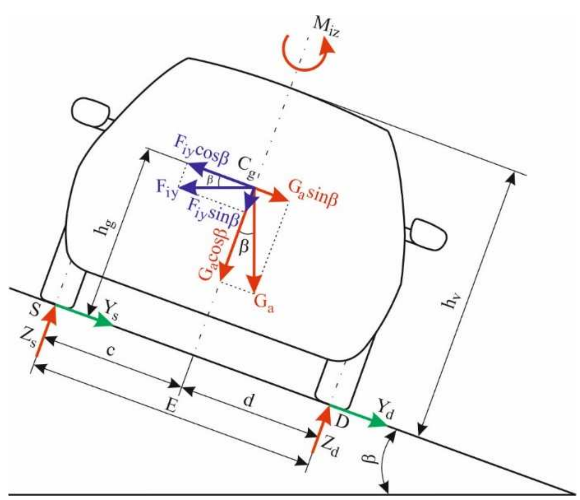


Fig. 1. The forces and moments acting on the vehicle with rigid suspension when cornering on a road with transverse slope β.

Other notations used in Figure 1 refer to: C_g which is the center of gravity of the vehicle; c, d - the position of the vehicle's center of gravity relative to its left and right sides, respectively; M_{iz} - the moment of inertia about the z-axis (yaw moment of inertia); $Y_{s,d}$ - the lateral reactions of the road on the vehicle's wheels (transverse grip components), on the left and right sides, respectively; $Z_{s,d}$ - the normal reactions of the road on the vehicle's wheels, on the left and right sides, respectively.

If the transverse inclination of the road is known as the slope p_β, expressed in %, then the angle β of the transverse inclination of the road, in degrees, will be taken into account according to the relation [17, 18]:

$$\beta = \text{arctg}\left(\frac{p_\beta}{100}\right). \quad (3)$$

For the variant of the elastic suspension (Fig. 2) [7, 8, 19], the SSF is determined from the equation of moments with respect to the rollover point S, taking into account the condition of maintaining transverse stability at rollover limit (normal reaction of the road on the wheels on the right side, $Z_d = 0$), according to the relation [8]:

$$\text{SSF}_{es} = \frac{a_y}{g} = \frac{\text{SSFa} + \text{SSFb}}{\text{SSFc} + \text{SSFd}}, \quad (4)$$

and the limit speed v_{aes_r} of the vehicle while turning on a road with a transverse slope, where the lateral rollover does not occur, but can start, is obtained from the relation [6, 7, 9-11]:

$$v_{aes_r} = \sqrt{g \cdot R \cdot \frac{\text{SSFa} + \text{SSFb}}{\text{SSFc} + \text{SSFd}}}, \text{ [m/s]}, \quad (5)$$

in which [7, 8]:

$$\text{SSFa} = m_e \cdot \left\{h_e \cdot \sin\beta + \left[\frac{E}{2} - (h_e - h_o) \cdot \Theta_v\right] \cdot \cos\beta\right\}, \quad (6)$$

$$\text{SSFb} = m_r \cdot \left[\frac{E}{2} \cdot \cos\beta + h_r \cdot \sin\beta\right], \quad (7)$$

$$\text{SSFc} = m_e \cdot \left\{h_e \cdot \cos\beta - \left[\frac{E}{2} - (h_e - h_o) \cdot \Theta_v\right] \cdot \sin\beta\right\}, \quad (8)$$

$$\text{SSFd} = m_r \cdot \left[h_r \cdot \cos\beta - \frac{E}{2} \cdot \sin\beta\right], \quad (9)$$

$$\Theta_v = \xi + \upsilon, \quad (10)$$

where [19]: Θ_v is the lateral angle of inclination in the turn of the suspended part, in rad; ξ - the angle with which the suspended mass is tilted in relation to the axis of the wheels, in rad; υ - inclination angle of the wheel axis in relation to the road, in rad; m_e - suspended mass; m_r - mass of the rigid assembly; $m_a = m_e + m_r$; h_e and h_r - the height of the centers of gravity of the suspended mass and the rigid mass; h_o - the height of the oscillation point O; $F_{iy_e} = m_e \cdot a_y$; $F_{iy_r} = m_r \cdot a_y$.

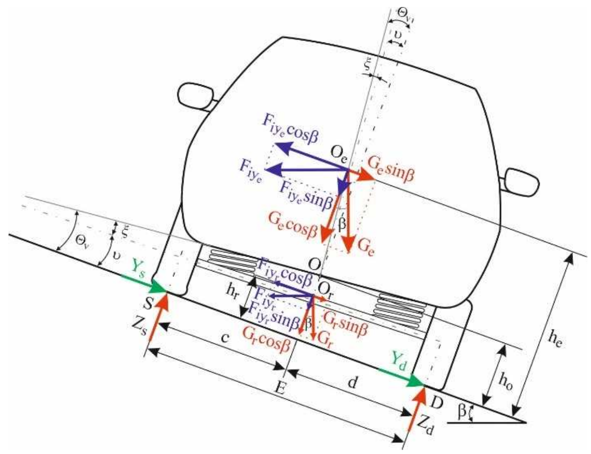


Fig. 2. Scheme for determining the Static Stability Factor, taking into account the transverse inclination of the road and the elasticity of the suspension.

Point O_e in figure 2 refers to the center of rotation of the suspended mass, and point O_r to the center of gravity of the rigid mass. Due to the elasticities of the suspension and the wheel tires, the center of gravity (see Fig. 2) [7, 8, 19] moves to the outside of the curve, and the weight of the suspended mass G_e additionally generates a destabilizing moment.

Transversal rollover of the vehicle is possible under the conditions shown above, if it is not preceded by lateral sliding (skid).

Based on the condition of maintaining the transverse stability during skidding ($\varphi_y \cdot (Z_s + Z_d) \geq Y_s + Y_d$) [12, 13, 16, 18, 20, 21] (see Fig. 1 and Fig. 2), taking into account the expression of the inertial force F_{iy}, we obtain the limit speed v_{a_d} of a vehicle in a cornering, on a road with a transverse slope, where skidding (sideways sliding) does not occur, but can start, given by the relation [3, 7, 12, 13, 16-18, 20, 21]:

$$v_{a_d} = \sqrt{g \cdot R \cdot \frac{\varphi_y + \text{tg}\beta}{1 - \varphi_y \cdot \text{tg}\beta}}, \text{ [m/s]}, \quad (11)$$

where φ_y is the transverse grip coefficient ($\varphi_y \cong 0.8 \cdot \varphi$), φ being the longitudinal grip coefficient.

For side slip to occur before side rollover, it is necessary that $v_{a_d} < v_{ars_r}$ (see Fig. 1), respectively $v_{a_d} < v_{aes_r}$ (see Fig. 2) [7, 12, 13, 16-18, 20, 21].

3. REACHING THE POSITION OF NEUTRAL STABILITY

The Neutral Stability Position (NSP) of the vehicle [8, 19] is reached when its center of gravity is on the vertical that passes through the contact point of the wheels with the road (Fig. 3) $\begin{pmatrix} F_t \cdot \cos\beta - G_a \cdot \sin\beta = Y_s \cdot \cos\beta - Z_s \cdot \sin\beta; \\ F_t \cdot \sin\beta + G_a \cdot \cos\beta = Y_s \cdot \sin\beta + Z_s \cdot \cos\beta \end{pmatrix}$.

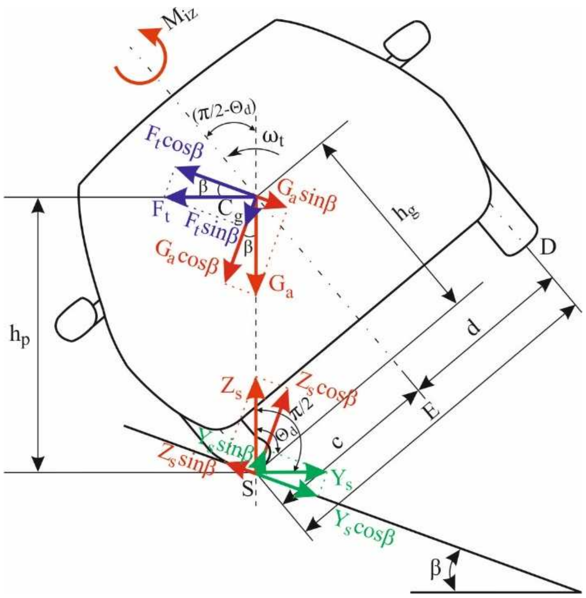


Fig. 3. Scheme for determining the conditions for reaching the Neutral Stability Position, taking into account the transverse inclination of the road.

After the wheels inside the curve lose contact with the road surface, the center of gravity of the vehicle moves towards the NSP, and reaching the NSP is conditioned by an impulse of a tangential force F_t ($F_t > G_a \cdot 0.50 \cdot E/h_g$) which manifests itself for the corresponding duration (< 0.80 s) of moving the center of gravity in the NSP [3, 8, 19].

For the rollover to happen, the vehicle must possess an energy that causes the center of gravity to rise from h_g to h_p (h_p being the height of the center of gravity in NSP, $h_p = \sqrt{(E/2)^2 + h_g^2}$) and at the same time overcome the inertia of its mass along this route [8, 19].

The notation Θ_d in figure 3 refers to the rotation angle of the vehicle's center of gravity C_g up to the Neutral Stability Position, which can be determined according to the relation [8, 9, 19]:

$$\Theta_d = \frac{\pi}{180} \cdot \left(90 - \text{arctg}\frac{2 \cdot h_g}{E}\right), \text{[rad]}. \quad (12)$$

The minimum speed required to reach the NSP, in m/s, can be found taking into account (see Fig. 3):

– translating the weight of the vehicle to the height (h_p–h_g) [3, 8, 19],

$$v_{NSP_t} = \sqrt{2 \cdot g \cdot h_g \cdot \left[\sqrt{\left(\frac{E}{2 \cdot h_g}\right)^2 + 1} - 1\right]}; \quad (13)$$

– the rotation of the vehicle's center of gravity until reaching the neutral stability angle Θ_d, [7, 8, 19],

$$v_{NSP_r} = \sqrt{\frac{2 \cdot g}{h_g} \cdot \left\{\frac{h_v + h_g}{K_v} \cdot E + \left[\left(\frac{E}{2}\right)^2 + h_g^2\right]\right\} \cdot \left[\sqrt{\left(\frac{E}{2 \cdot h_g}\right)^2 + 1} - 1\right]}, \quad (14)$$

where: h_v represents the height of the vehicle; K_v - coefficient of the mass moment of rolling inertia, whose values depend on the type of vehicle (for passenger cars, K_v = 7.9846 [6, 8, 19]);

– the force of the minimum impulse to reach the NSP, F_t [8, 19],

$$v_{NSP_f} = \sqrt{\frac{2F_t \cdot \Theta_d}{m_a} \cdot \sqrt{\left(\frac{E}{2 \cdot h_g}\right)^2 + h_g^2}}. \quad (15)$$

4. OBTAINED RESULTS

For illustration, in the numerical calculation model developed using MathCAD, the determination of SSF, slip and rollover limit speeds, and the minimum speed necessary to reach the NSP is sought, depending on the transverse inclination of the road, considering the input data captured in Table 1 [19]. The developed working algorithm allows obtaining results graphically.

The results obtained regarding SSF (Fig. 4) indicate that, generally, the Static Stability Factor has average values of approximately 1.10 for vehicles with rigid suspension and approximately 0.85 for vehicles with elastic suspension, falling within the recommended range of 0.85 to 1.40 [8, 19].

Table 1

Input Data [19]

Parameter	Notation	Adopted Values		UM
		Vehicle 1	Vehicle 2	
❑ Mass of the vehicle	m_a	1250		kg
❑ Mass of the suspended part	m_e	1020		kg
❑ Mass of the rigid assembly	m_r	230		kg
❑ Track width	E	1.35		m
❑ Overall height	h_v	1.25	1.60	m
❑ Height of the gravity center	h_g	0.55	0.75	m
❑ Height of the gravity center of the suspended part	h_e	0.75	0.85	m
❑ Height of the gravity center of the rigid part	h_r	0.30		m
❑ Height of the center of oscillation of the suspended part	h_0	0.35		m
❑ Lateral tilt angle in cornering of the suspended part	Θ_v	0.253		rad
❑ Coefficient of mass moment of roll inertia	K_v	7.9846		-
❑ Coefficient of longitudinal grip	φ	0.75		-
❑ Coefficient of transverse grip	φ_y	0.60		-
❑ Transverse slope of the road	p_β	0; 0.5; 1, 1.5; 2.5; 3		%
❑ Radius of trajectory curvature traveled by the vehicle	R	50; 100; 150		m

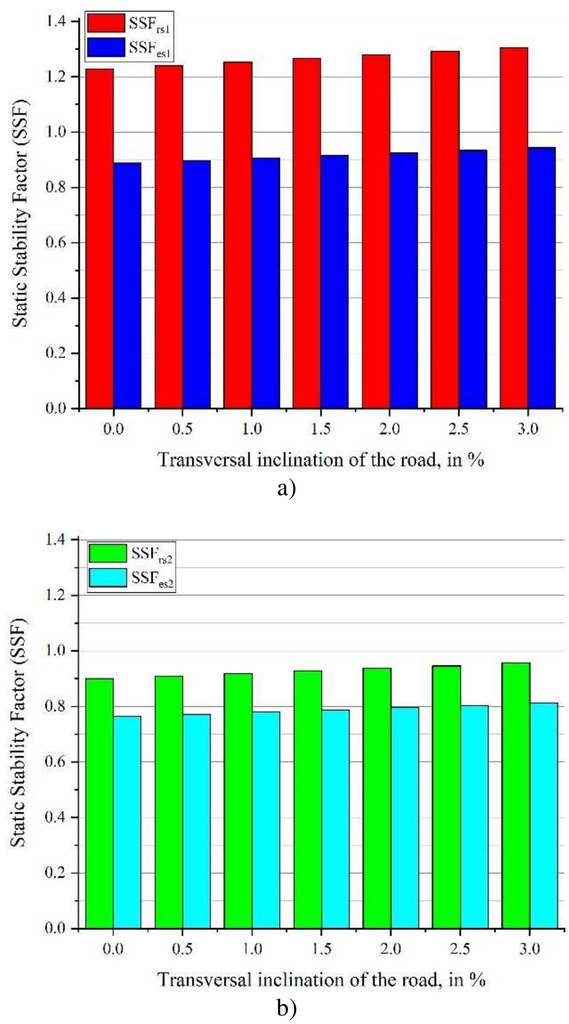
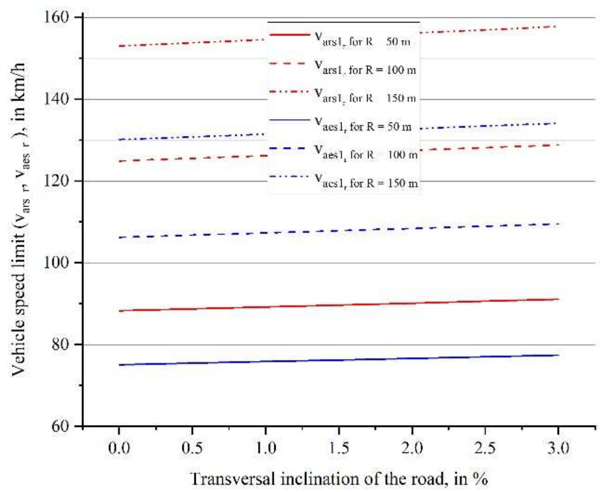


Fig. 4. Variation of the Static Stability Factor of vehicles, depending on the transverse inclination of the road.
a - vehicle 1; b - vehicle 2.

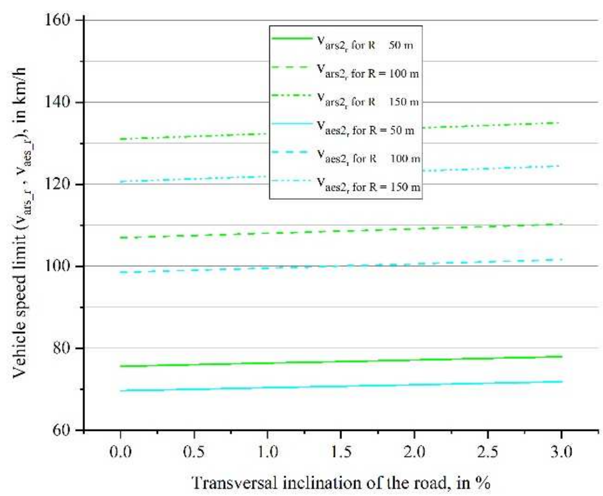
With regard to the speed limit of the considered vehicles in cornering, on a road with a transverse slope, where skidding (sideways sliding) v_{a_d}, does not occur, but can begin, the results obtained (Fig. 5, Fig. 6, Fig. 7) show that this is lower than the limit speed of their displacement under the same conditions, at which the lateral rollover v_{a_r}, does not occur, but can begin. Thus, $v_{a_d} < v_{a_r}$ (see Fig. 7), which indicates that the loss of stability of the considered vehicles will be manifested in the first phase by skidding, the rollover being preceded by lateral sliding.

Also, both v_{a_d} and v_{a_r} (see Fig. 5, Fig. 6) increase with the transverse slope of the road, which confirms that the slope of the road surface inclined towards the inside of the curve is necessary in road construction [16], in order to maintain the vehicle's stability when turning.

With regard to the minimum speed necessary to reach the NSP (see Fig. 3), the results are also captured in [19], and in figure 8 the values obtained [19] for this speed are shown comparatively, based on relations (13), (14) and (15).



a)



b)

Fig. 5. The variation of the speed limit of vehicles movement in cornering, on a road with a transverse slope, at which rollover does not take place, but may start, depending on the transverse slope of the road.
a - vehicle 1; b - vehicle 2.

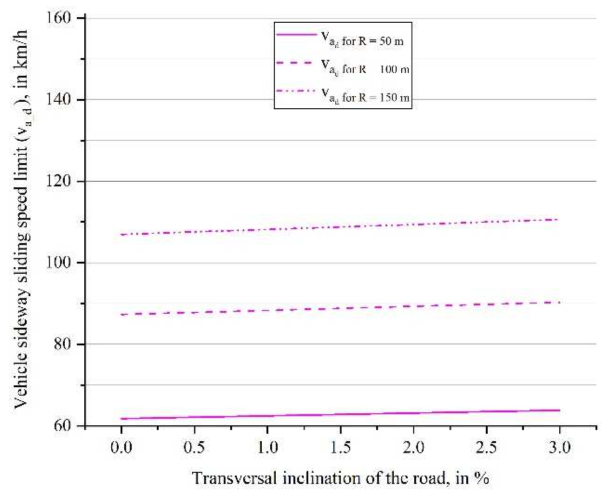


Fig. 6. The variation of the speed limit of a vehicle in cornering, on a road with a transverse slope, at which skidding (sideways sliding) does not occur, but may begin, depending on the transverse slope of the road.

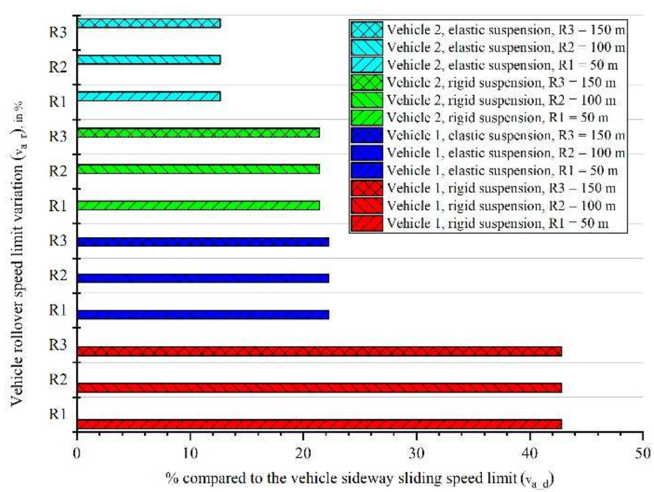


Fig. 7. The variation of the speed limit of movement of vehicles in cornering, on a road with a transverse slope, where the lateral rollover does not occur, but may start, depending on the speed limit of vehicle movement in cornering, on a road with transverse inclination, at which it does not occur, but skidding (sideways sliding) may begin.

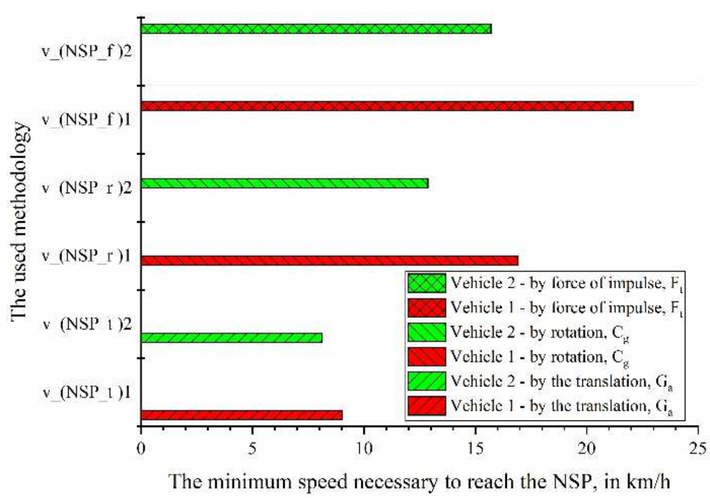


Fig. 8. The minimum speed necessary to reach the NSP.

Comparing the methodologies used to identify the minimum speeds at which it is possible to reach the NSP, in the case of the considered vehicles, the differences between the speeds of the two vehicles are approximately 10%, if the translation of the weight of the vehicle on the height (h_p–h_g), is taken into account, of approximately 24% if the rotation of the vehicle's center of gravity is taken into account until reaching the neutral stability angle Θ_d and of approximately 29% if the minimum impulse force to reach the NSP, F_t is taken into account (see Fig. 3). Thus, whatever the methodology used in this regard, the differences between the minimum speeds at which it is possible to reach the NSP are maintained at these proportions, depending on the centers of gravity heights of the vehicles [19]. In the case of the vehicle with a higher height of the center of gravity, a lower minimum speed is required to reach the NSP [19] than in the case of the vehicle with a lower height of the center of gravity.

5. CONCLUSIONS

The Static Stability Factor sets the limit value when the vehicle overturns, and exceeding it can lead to the vehicle rollover.

The results obtained show that a rigid suspension (or one with variable stiffness that increases with inclination) provides a higher Static Stability Factor than the elastic one, so the risk of rollover is lower in the case of vehicles with rigid suspension compared to those with elastic suspension.

Also, the obtained results capture the mutual influences of the parameters that characterize the transversal stability of the vehicles.

The angle of transverse inclination of the road and the speed of the vehicle are in a proportional relation.

The dimensional and weight parameters of the vehicle, the turning radius of the traveled route by the vehicle and the speed with which the vehicle enters in cornering, directly influence its transverse stability.

The speed limit for vehicle rollover in cornering can be increased with the increase of the turning radius of the traveled route by the vehicle and the angle of transverse inclination of the road.

The developed working algorithm can be applied for any type of vehicle and any driving conditions on the road with a transverse slope.

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EVALUAREA INFLUENȚEI ÎNCLINĂRII TRANSVERSALE A CĂII DE RULARE ASUPRA PARAMETRILOR STABILITĂȚII AUTOVEHICULELOR LA LIMITA RĂSTURNĂRII LATERALE

Rezumat: În lucrare se evaluează, din punct de vedere fizico-matematic, parametrii stabilității transversale a autovehiculelor la răsturnare, cu referire la factorul de stabilitate statică a acestora, luând în considerare influența înclinării transversale a drumului și posibilitatea atingerii poziţiei de stabilitate neutră. De asemenea, se evaluează vitezele de deplasare ale autovehiculelor la care nu are loc, dar poate începe deraparea, respectiv răsturnarea laterală. Algoritmul de lucru s-a dezvoltat ținând seama de forțele care acționează asupra autovehiculului aflat în viraj, poziţia centrului de greutate al autovehiculului, masa acestuia, unghiul de înclinare transversală a drumului, raza de viraj a traseului parcurs de autovehicul și parametrii constructivi ai autovehiculului.

Irina DUMA, PhD Student, Eng., Assistant, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, irina.duma@auto.utcluj.ro, Office Phone 0264 401 779.

Nicolae BURNETE, PhD. Eng., Professor, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, nicolae.burnete@auto.utcluj.ro, Office Phone 0264 401 779.

Adrian TODORUȚ, PhD. Eng., Professor, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, adrian.todorut@auto.utcluj.ro, Office Phone 0264 401 674.

Nicolae CORDOȘ, PhD. Eng., Associate Professor, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, nicolae.cordos@auto.utcluj.ro, Office Phone 0264 401 779.

István BARABÁS, PhD. Eng., Professor, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, istvan.barabas@auto.utcluj.ro, Office Phone 0264 401 674.

Andreia MOLEA, PhD. Eng., Lecturer, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, andreia.molea@auto.utcluj.ro, Office Phone 0264 401 779.

Marian-Daniel DRAGOSTE, PhD Student, Eng., Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, daniel.dragoste@auto.utcluj.ro, Office Phone 0264 401 779.

Radu-Mihai EFRIM, PhD Student, Eng., Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, radu.efrim@auto.utcluj.ro, Office Phone 0264 401 779.

Alexandru TEREC, PhD Student, Eng., Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanics, Department of Automotive Engineering and Transports, Romania, alexandru.terec@auto.utcluj.ro, Office Phone 0264 401 779.