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WAYS TO EVALUATE THE TRANSVERSAL STABILITY PARAMETERS OF THE VEHICLES

Adrian TODORUŢ, Nicolae CORDOŞ, Monica BĂLCĂU

Abstract: *The paper presents an analytical study using numerical modelling, regarding the evaluation of transversal stability parameters of vehicles. When developing the numerical model used we took into account: the forces acting on a vehicle engaged in turning; the influence of the vehicle's centre of gravity as well as its weight on its moving velocity and its transversal stability; the influence of the angle of the transversal incline of the road on the vehicle's velocity and stability; the influence of the turning radius on the vehicle's velocity and stability. The study takes into account aspects related to various transversal road inclinations, various trajectory radiuses, various velocities and the main parameters of the vehicles taken into consideration. The results obtained are in a graphic form and they depict the vehicle's transversal stability in the case of the transversal profile with a unique slope and in the case of the transversal profile with two plane slopes.*

Key words: *vehicle, transversal stability, numerical modelling*

1. INTRODUCTION

Other studies on the vehicles stability are presented in [1-12], in which by using dynamic and numerical models or by doing experiments and simulation one obtains remarkable results on their dynamics, their control and maintaining balance during movement.

The loss of transversal vehicle stability can occur either by its slide slipping (lateral sliding), or by its lateral turnover [4-12]. If the transversal inclination of the road is high, the vehicle's sliding or tipping over sideways can occur even if the vehicle moves in a straight line [3].

The study presented in this paper takes into account the running conditions (the nature and the state of the road, its transversal inclination, the route's radius, etc) and the forces that act on these, while the various running situations are depicted in physical and mathematical models.

In order to evaluate the transversal stability parameters of the vehicles, we constructed several numerical computational models that take into account the physical phenomena that take place when the vehicles move in various running conditions and that allow the user to interpret the results in a graphical interpretation. The numerical algorithm was developed using MathCAD and takes into account the constructive parameters of the vehicle, as well as various running conditions, such as geometry, nature and state of the road, etc.

2. NUMERICAL EVALUATION METHOD

2.1. Notations used in the numerical computation model

To exemplify, the numerical computational model takes into account a vehicle with the following data: the markings on the tyres, 195/65 R 15; the pressure in the tyres, 0.22 MPa; the mass of the vehicle, m_a=1740 kg; the wheelbase, A=2.511 m; height, H=1.479 m; total length, B=4.199 m; front gauge, E_1=1.540 m; rear gauge, E_2=1.513 m; maximum velocity, v_{max}=180 km/h.

Of the variables used in the numerical computation model we mention:

- φ is the longitudinal adhesion coefficient and φ_{y_k} is the transversal adhesion coefficient, given by the nature and the state of the road, k=1…2 - is the variable that characterises the road taken into account (k=1 - for a road of dry concrete asphalt, k=2 - for a road of wet dirty concrete asphalt);

- the height of the centre of gravity of the vehicle, $h_g \cong 0.21 \cdot A$;
- the turn radius, R_i, i=1…3 - the variable that characterises the turn radius (i=1 - for a radius of 100 m, i=2 - for a radius of 200 m, i=3 - for a radius of 300 m);
- the angle of transverse slope of the road, β_j = 1°, 2°, 3°, 4°, j=1…4 the variable that characterises the angle of the transverse slope of the road (j=1 - pentru unghi de 1°, j=2 for an angle of 2°, j=3 - for an angle of 3°, j=4 - for an angle of 4°);
- the velocity of the vehicle, v_a = 10, 20, …, v_{max}, in km/h.

2.2. Evaluating the transversal stability of an overturned vehicle

To establish the criteria for the transversal stability, we take into account a vehicle that is turning on a road with a transversal slope of β. The transversal overturning of the vehicle is produced with reference with point C (Fig. 1) [2, 7-12].

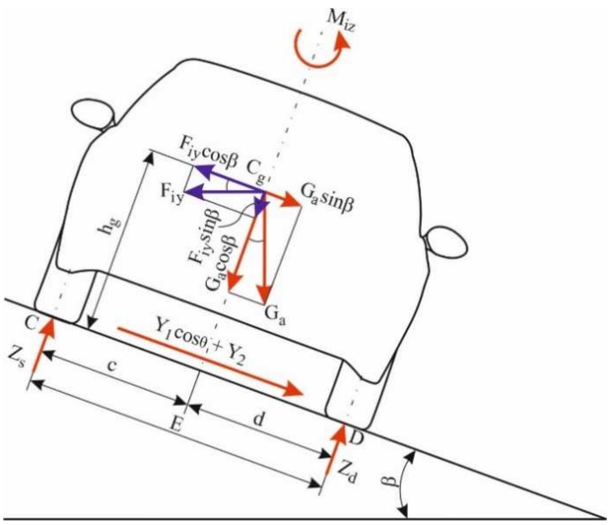

Fig. 1. The forces and momentums that act on the vehicle when moving in the turn on a road with a transversal slope β.

The markings in figure 1 refer to: E - the wheelbase of the vehicle; c, d - the position of the centre of the gravity of the vehicle in relation to its left, respectively right side; C_g - centre of gravity; h_g - height of the centre of gravity; β - the transversal inclination angle of the road; F_{iy} - the transversal inertial force; M_{iz} - inertial moment on axis z (the moment of resistance to girder); θ - the steering angle of the steering wheels; $Y_{1,2}$ - lateral reactions of the road on the wheels of the vehicle (transversal adherence components); $Z_{s,d}$ - normal reactions of the road on the roads of the vehicle on both left and right side.

Taking into account that the velocity of the vehicle v and the turn radius R are constant, based on the equation of the momentum from the turning point C (see Fig. 1), and taking into account the inertial force F_{iy}, $F_{iy} = G_a \cdot v_a^2/(g \cdot R)$ and given the condition of maintain the transversal stability at the limit ($Z_D = 0$), we obtain [7, 8, 10-12] the limit of the transversal angle of the road β_r, where the transversal turning stability is at its limit, the overturning of the vehicle at this angle being possible at any moment.

$$\beta_{r_{i,va}} = arctg\left(\frac{\frac{v_a^2}{g \cdot R_i} - \frac{E}{2 \cdot h_g}}{1 + \frac{v_a^2}{g \cdot R_i} \cdot \frac{E}{2 \cdot h_g}}\right), \qquad (1)$$

where: v_a is the velocity of the vehicle, in m/s; g - gravitational acceleration, in m/s^2; h_g - the height of the centre of gravity of the vehicle, in m; R - turning radius, in m; E - wheelbase, in m.

The limit velocity v_{cr_r} of the vehicle in a turn, on a road with a transversal slope, which does not take place but can begin the side overturning, is given by the relation [7, 8, 10-12]:

$$v_{cr_{r_{i,j}}} = \sqrt{\frac{g \cdot R_i \cdot \left(\frac{E}{2 \cdot h_g} + tg\beta_j\right)}{1 - \frac{E}{2 \cdot h_g} \cdot tg\beta_j}}\,. \qquad (2)$$

Some of the observations worth mentioning here are: an increase in the transversal angle of the road β will be met by an increase in the velocity v_{cr_r}; at $tg\beta = \frac{2 \cdot h_g}{E}$, thus resulting $v_{cr_r} \to \infty$, without the overturning to take place; the transversal inclination, with a slope that rises towards the exterior of the curve is applied to the modern roads; at $\beta = 0 \Rightarrow v_{cr_r} = \sqrt{\frac{g \cdot R \cdot E}{2 \cdot h_g}}$, in m/s.

The transversal overturning of the vehicle is possible in the conditions shown above if it is not preceded by a sideslip.

2.3. Evaluating the transversal stability when the vehicle is side slipping

Taking into account that the velocity of the vehicle v_a and the turn radius R are constant, based on the condition of maintaining the transversal stability when slide slipping, $\varphi_y \cdot (Z_s + Z_d) \geq Y_1 \cdot \cos\theta + Y_2$ [3, 7, 8, 10-12] (see Fig. 1) and taking into account the expression of the inertial force F_{iy}, we obtain the limit of the transversal inclination of the road β_d, where the transversal stability when slipping is at a limit (at this angle the vehicle is still maintaining its transversal stability when slipping on a side, but the side slipping is possible at any moment) [7, 8, 11, 12]:

$$\beta_d(i,k,v_a) = arctg\left(\frac{\frac{v_a^2}{R_i} - \varphi_{y_k} \cdot g}{g + \varphi_{y_k} \cdot \frac{v_a^2}{R_i}}\right), \quad (3)$$

where φ_y is the transversal adherence coefficient ($\varphi_y \cong 0{,}8 \cdot \varphi$).

The maximum velocity v_{cr_d} of a vehicle when turning, on a road with a transversal inclination which doesn't take place but the sideslip can happen at any moment is given by the relation [7, 8, 11, 12]:

$$v_{cr_d}(i,k,j) = \sqrt{\frac{g \cdot R_i \cdot (\varphi_{y_k} + tg\beta_i)}{1 - \varphi_{y_k} \cdot tg\beta_i}}. \quad (4)$$

Of the observations worth mentioning there: the increase in the transversal inclination of the road β will also be met by an increase in the velocity v_{cr_d}; at $tg\beta = \frac{1}{\varphi_y}$, thus resulting $v_{cr_d} \to \infty$, wihout the sideslip to take place; at $\beta = 0 \Rightarrow v_{cr_d} = \sqrt{\varphi_y \cdot g \cdot R}$, m/s.

Considering that the sideslip of the vehicle is not as dangerous as the overturning, provided that the sideslip takes place before the lateral overturning ($v_{cr\,d} < v_{cr\,r}$ sau $\beta_d < \beta_r$) we obtain [7, 8, 11, 12]:

$$\varphi_y < \frac{E}{2 \cdot h_g}. \quad (5)$$

The relation (5) is always true, even at high values of φ_y. Consequently, the loss of lateral stability of a vehicle is most frequently characterised by a side slip and not a lateral overturning.

The conditions for the lateral stability shown above are valid in the situation when the wheels of the vehicle are not being acted on by traction or braking tangential forces. In reality, both the slide slip and the transversal overturning of a vehicle take place faster than the values obtained in the respective conditions.

2.3.1. Evaluating the transversal stability parameters of vehicles by means of transversal adherence

Controlling the side slipping by means of transversal adherence. A vehicle that covers a curved area of radius R on a road without transversal inclination is acted upon by centrifugal force F_{cf} [3, 10], the lateral transversal adherence force (Y_s+Y_d), normal reactions of the road on the wheels (Z_s+Z_d) and its own weight G_a (Fig. 2).

In order to avoid sliding, the condition must be met [3, 10]:

$$F_{cf} \leq (Y_s + Y_d). \quad (6)$$

At limit, the radius of the area covered by the vehicle is determined by the relation [3, 10]:

$$R_{t_{k,v_a}} = \frac{v_a^2}{\varphi_{y_k} \cdot g}, \text{ in m}, \quad (7)$$

$$v_{at_{i,k}} = \sqrt{\varphi_{y_k} \cdot g \cdot R_i}, \quad (8)$$

where: R is expressed in m, v - in m/s, and g - in m/s^2.

2.3.2. Evaluating the transversal stability parameters of the vehicle in the case of a transversal profile with a unique slope

Controlling the side slipping by adding an overhanging to the road area. In theory, the unique transversal inclination of the road that would completely annihilate the effects of the centrifugal force without taking into account the contribution of the adherence between the wheels and the surface of the road (the ideal or theoretical overhanging) would be [3, 10] the one for which the result R_{cfg} of the two forces F_{cf} and G_a would act normally on the surface of the road (Fig.3) and thus parallel to the road, the one that causes the slipping, would be nil. In the case of vehicles running with a lower velocity, the result R_{cfg} is no longer perpendicular on the surface of the road but it is rather guided towards the interior, and in this case there is a tendency for slipping or overturning towards the interior of the curve. This is why overhanging the road is limited.

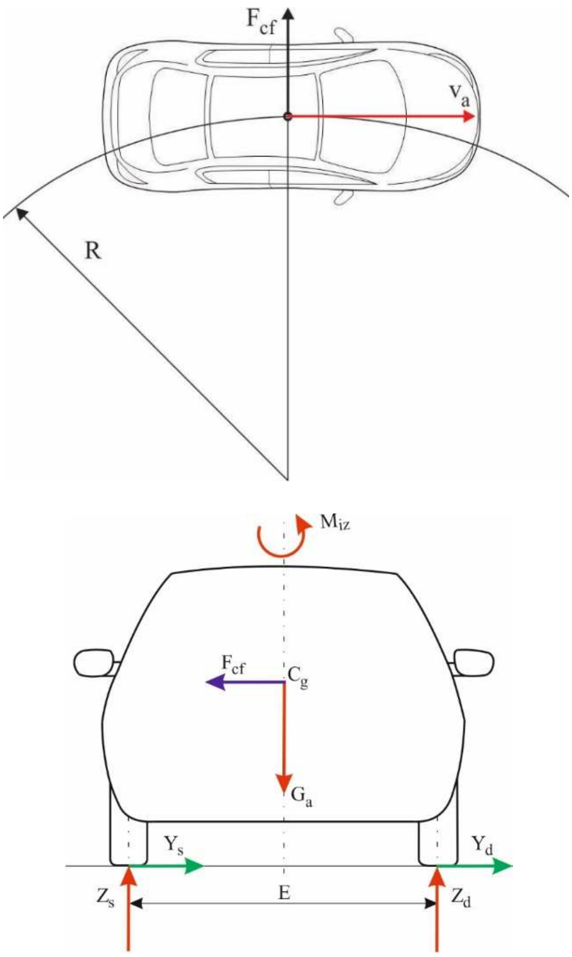

Fig. 2. Controlling the side slipping by using the transversal adherence.

In this case, the cant results this way [3, 10]:

$$p_\beta[\%] = 100 \cdot tg\beta = 100 \cdot \frac{F_{cf}}{G_a} = 100 \cdot \frac{\frac{m_a \cdot v_a^2}{R}}{m_a \cdot g} = 100 \cdot \frac{v_a^2}{g \cdot R}, \quad (9)$$

where: R is expressed in m; v_a - in m/s; g - in m/s^2.

From relation (9), results [3, 10] the radius of the area covered by the vehicle, according to the relation:

$$R_{s\,j,v_a} = \frac{v_a^2}{g \cdot p_{\beta_j}[\%]} \cdot 100, \text{ in m,} \quad (10)$$

$$v_{as_{i,j}} = \sqrt{\frac{g \cdot R_i \cdot p_{\beta_j}[\%]}{100}}, \text{ in m/s.} \quad (11)$$

In practice, however, controlling the side slipping only by overhanging the road is not possible because it leads to highly exaggerated values of the lateral inclination [3, 10].

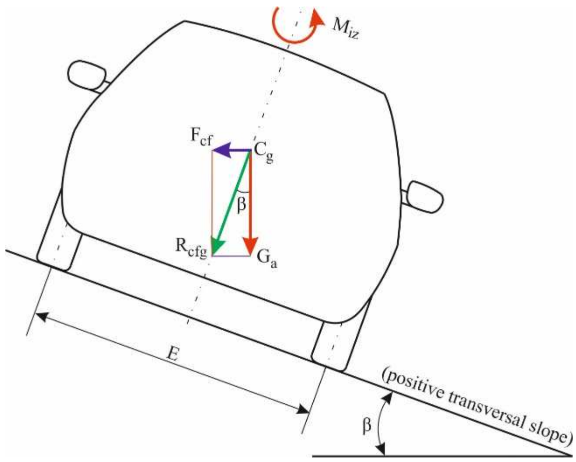

Fig. 3. Ensuring the stability of the vehicle in a curve by overhanging.

The slipping must be controlled by a simultaneous action of overhanging the road and the adherence between the wheels of the vehicle and the road (in order to reach satisfactory results that would correspond to real situations we must take into account both adherence and overhanging at the same time).

The lower the influence of the adherence in relation to the overhanging, the higher the comfort when driving.

2.3.3. Evaluating the transversal stability of the vehicle in the case of a transversal profile with two plane slopes

Controlling the side slipping both by transversal adherence and the overhanging the road. In this case, the vehicles on the outer lane are on a negative overhanging [3, 10], the inclination of the road supporting the slipping (Fig. 4). As a consequence, we have components of weight and centrifugal force, both parallel and perpendicular to the road surface. Also, lateral adherence forces are created between the wheels and the road.

In the case of the vehicle on a road with a positive/negative overhanging (see Fig. 4), from the condition of stability in a curve, $Y_1 \cdot \cos\theta + Y_2 \leq \varphi_y \cdot (Z_s + Z_d)$ [3, 7, 8, 10-12], results:

$$F_{cf}\cdot cos\alpha - G_a\cdot sin\beta \le$$
$$\le \varphi_y\cdot\left(G_a\cdot cos\alpha + F_{cf}\cdot sin\beta\right), \qquad (12)$$

in the case of positive overhanging and,

$$F_{cf}\cdot cos\alpha + G_a\cdot sin\beta \le$$
$$\le \varphi_y\cdot\left(G_a\cdot cos\alpha - F_{cf}\cdot sin\beta\right), \qquad (13)$$

in the case of negative overhanging.

For low values of the angle β, the approximations can be taken into account [3]: cosβ≅1, and sinβ≅tgβ≅p_β, where p_β is the overhanging, $p_\beta = \frac{p_\beta[\%]}{100}$. Thus, to control the sliding in the case of positive/negative overhanging, we can use the relation [3]:

$$F_{cf} \mp G_a\cdot p_\beta \le \varphi_y\cdot G_a \pm \varphi_y\cdot F_{cf}\cdot p_\beta, \qquad (14)$$

but the product $\left(\varphi_y\cdot F_{cf}\cdot p_\beta\right)$, being very little, can be neglected.

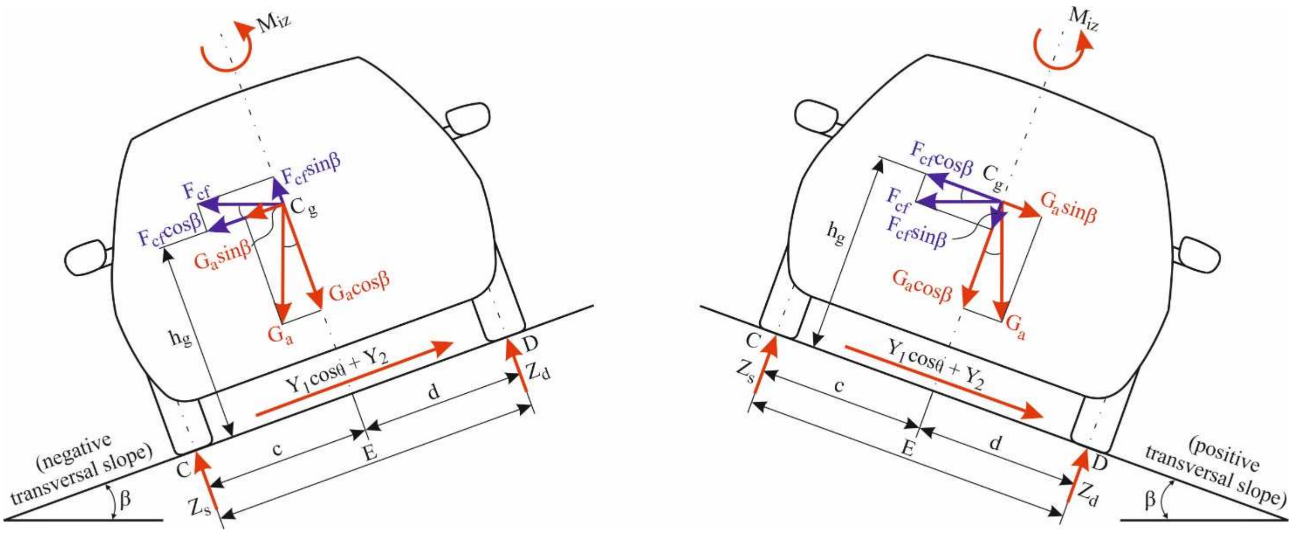

Fig. 4. Ensuring the stability of the vehicle in a curve in the case of a transversal profile with two plane slopes (traffic also on the negative overhanging). F_{cf} - centrifugal force.

Then, in order to control the slipping in the case of positive/negative overhanging, the condition [3, 10] must be met:

$$\frac{G_a\cdot v_a^2}{g\cdot R} \mp G_a\cdot p_\beta \le \varphi_y\cdot G_a, \qquad (15)$$

$$\frac{v_a^2}{g\cdot R} \le \varphi_y \pm p_\beta, \qquad (16)$$

$$R_{d_n^p}(j,k,v_a) \ge \frac{v_a^2}{g\cdot\left(\varphi_{y_k} \pm p_{\beta_j}\right)}, \qquad (17)$$

$$v_{crd_n^p}(i,k,j) \le \sqrt{g\cdot R_i\cdot\left(\varphi_{y_k} \pm p_{\beta_j}\right)}, \qquad (18)$$

In relations (17) and (18), the sign (+) corresponds to the positive overhanging (p) and (−) to the negative one (n), (g - in m/s^2; v_a - in m/s).

3. RESULTS

The developed numerical computational model allows obtaining results with graphic interpretation. Figure 5 depicts the variation of the limit angles of transversal inclination of the road when slipping β_d and overturning β_r according to the velocity of the vehicle and the turn radius of the road. Taking into account that a vehicle slipping is less dangerous than a vehicle overturning, it is better for a vehicle to slip before overturning. If the value of the transversal inclination angle increases, the limit velocities of the vehicle in the turn, at which slipping/overturning doesn't take place but can always start increases (see Fig. 5). Based on the results obtained (see Fig. 5), one can notice the influence the road, respectively the transversal adherence have over the stability of the vehicle. Thus, in the second case of road taken into account, the wet dirty concrete asphalt, the maximum velocity of the vehicle diminishes significantly in comparison to the first case taken into account, the dry concrete asphalt road.

Another important parameter to evaluate the transversal stability during slipping and overturning is the limit velocity of the vehicle in a turn on a road with a transversal incline, where the lateral overturning can take place but doesn't (Fig. 6, Fig. 7).

One can observe that the limit velocities of the vehicle in turns on a road with a transversal incline, where there is no slipping or overturning but one may begin, increase with the increase of the turn radius (see Fig. 6), which can be applied when building the roads in order to optimise the curves and improve the performances of transversal stability. Also, the results show that the velocity at which the overturning can start to happen v_{cr_r} is higher than the limit velocity at which the slipping occurs v_{cr_d}, which indicates that the vehicle will slip first before overturning. Thus, when using vehicles, when referring to maintaining transversal stability, the condition is that the side slip to take place before the side overturn ($v_{cr_d} < v_{cr_r}$). The results obtained (see Fig. 7) show that the velocities v_{cr_r}, respectively v_{cr_d}, increase at the same time with the transversal incline of the road, with the slope going up towards the exterior of the curve, which must be taken into account when building the roads in order to optimise the areas with transversal inclination.

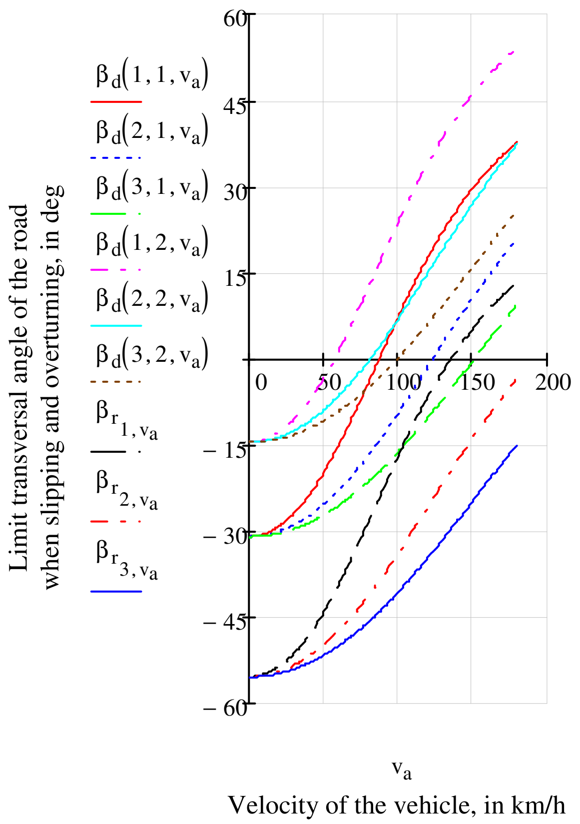

Fig. 5. Variation of the transversal limit angle of the road when slipping and overturning, according to the turning radius and the velocity of the vehicle in the case of the two roads taken into account.

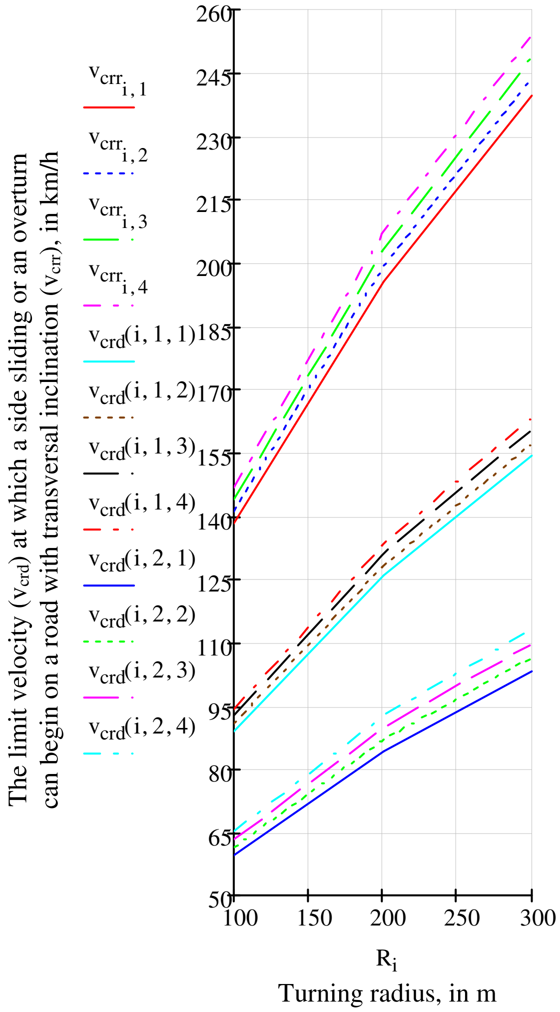

Fig. 6. Velocity variation of the vehicle when turning, on a road with a transversal inclination, at which the side overturn can commence, respectively the slipping (for various states of the road), according to the turning radius.

Considering that the overturning is far more dangerous than the slipping, it is preferable, from the stability point of view, that the vehicle slips before it overturns. The results related to controlling the side slipping both by transversal adherence and by overhanging the road are depicted in figures 8…13, where we took into account the influence of various states of the road (characterised by the adherence coefficient) on the turning radius, in the case of positive overhanging (Fig.8) and negative one (Fig.9), or on the limit velocity of the vehicle in the turn, in the case of positive overhanging (Fig. 10, 12) and negative (Fig. 11, 13). A piece of road characterised by a satisfactory adherence facilitates maintaining the transversal vehicle stability by the increase of the limit velocity in the transversal plane, or by reducing the turning radius.

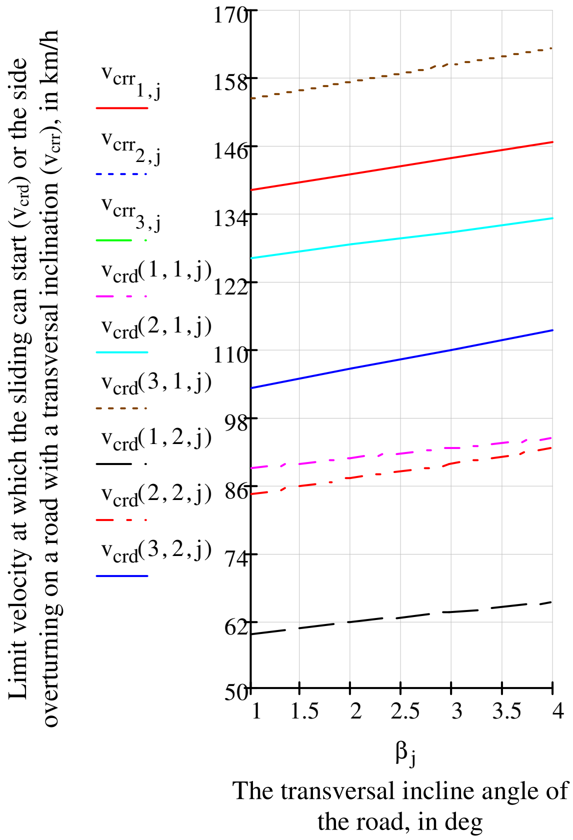

Fig. 7. Variation of the limit velocity of the vehicle when turning, on a road with a transversal inclination, at which the lateral overturn can begin, respectively the slipping (for various states of the road) according to the transversal inclination angle of the road.

4. CONCLUSIONS

Identifying the limits for maintaining the vehicles stability in various conditions, leads towards a new means to improve the performance of the vehicles. The studies on the evaluation of the transversal vehicles stability allowed us to draw some conclusions:

- the numerical computational model developed allows obtaining results with graphic interpretation, which capture the reciprocal influences of the parameters that characterise the transversal vehicles stability;
- the transversal vehicles stability is influenced directly by the dimensional parameters and their weight, by the turning radius of the road as well as by the velocity with which the vehicle engages in the turn;
- in the case of transversal stability when the vehicle is overturning, we notice that, at the same time with the increase of the limit angle of the transversal piece of road, the critical velocity of the vehicle also increases and the two values (the inclination angle and the velocity) are proportional;
- in the case of the transversal stability of the vehicle, by the effect of the transversal adherence, we notice that the velocity is directly influenced by the turning radius of the piece of road; the same influence takes place also in the context of transversal stability, when the transversal profile with a unique slope, respectively with two plane slopes, with the remark that in those cases we also take into account the transversal angle of the road; the turning radius increases with the increase of the velocity of the vehicle but also with the decrease of the transversal angle of the road; the limit velocity of the sliding in the turn of the vehicle in the case of positive overhanging increases with the increase of the transversal inclination angle, and in the case of negative overhanging, this one decreases with the transversal inclination angle of the road;
- in order for the vehicle to maintain its transversal stability, its velocity must be adapted according to the transversal inclination of the road and its category, the radius of the turn but also the dimensional parameters and the weight of the vehicle;
- the computational model developed can be adapted for any type of vehicle, as well as for other driving conditions.

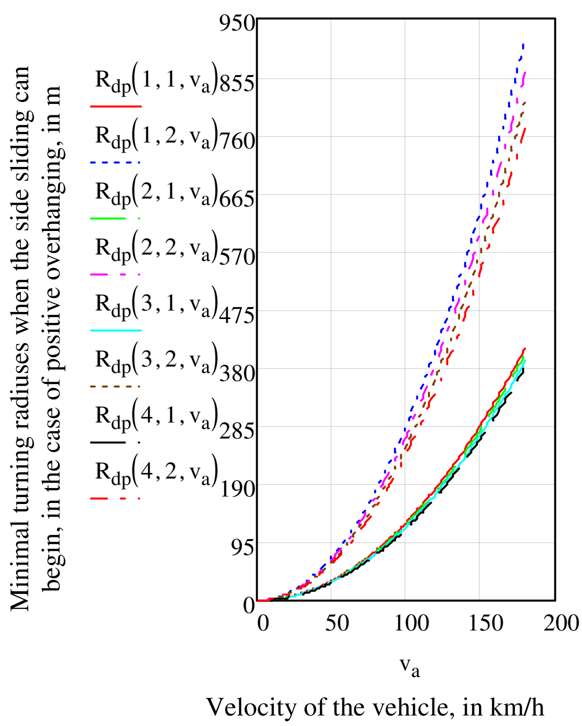

Fig. 8. Variation of minimal turning radiuses when the side sliding can begin, on a road with transversal inclination with *positive overhanging*, according to the velocity of the vehicle, in the case of various roads taken into account and various transversal inclinations.

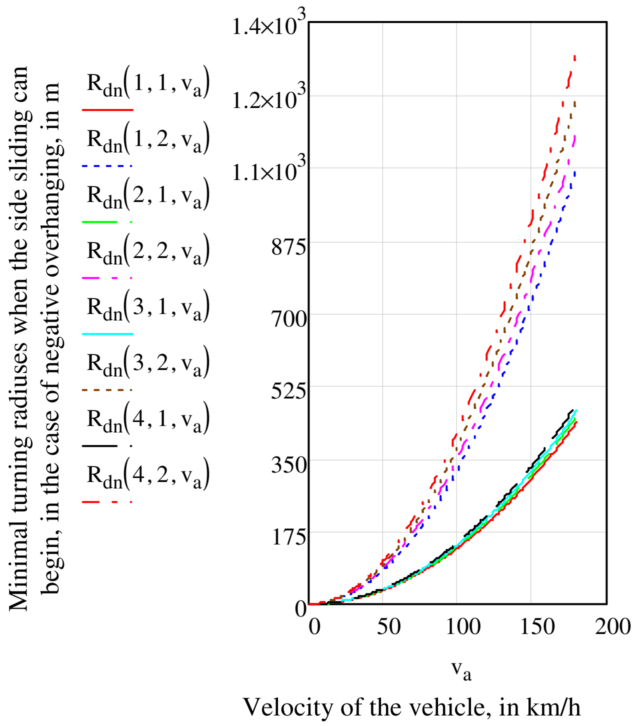

Fig. 9. Variation of minimal turning radiuses when the side sliding can begin, on a road with transversal inclination with *negative overhanging*, according to the velocity of the vehicle, in the case of various roads taken into account and various transversal inclinations.

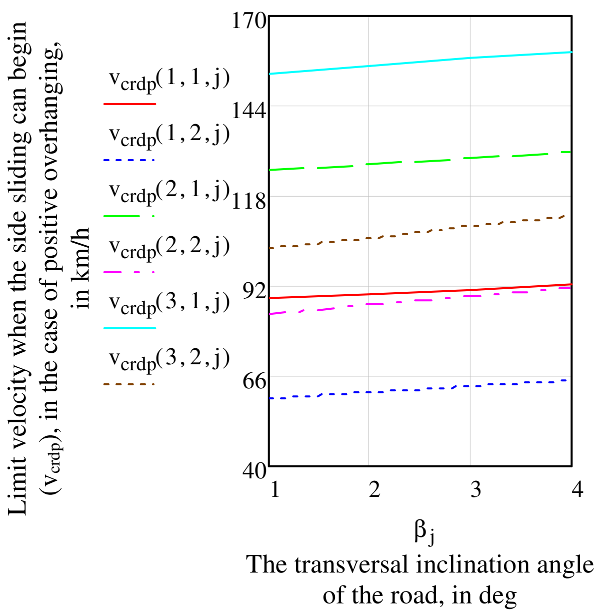

Fig. 10. Velocity variation of the vehicle in turning, at which the vehicle can begin to side slide on a road with transversal inclination with *positive overhanging*, according to the transversal inclination angle on various types of roads and various turning radiuses.

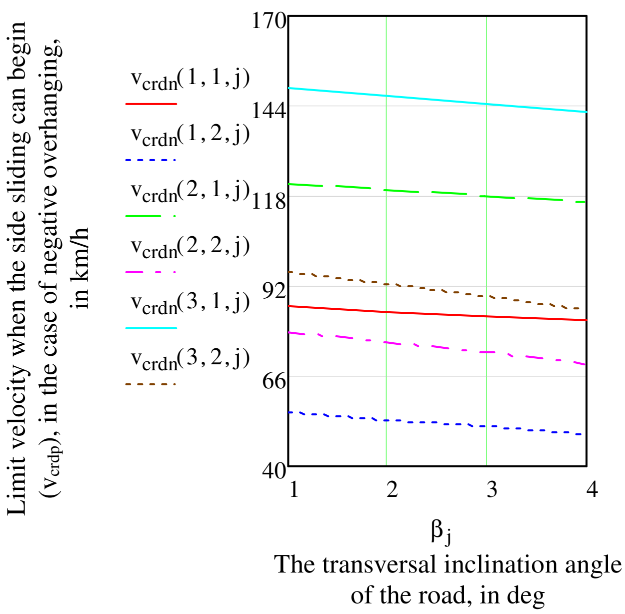

Fig. 11. Velocity variation of the vehicle in turning, at which the vehicle can begin to side slide on a road with transversal inclination with *negative overhanging*, according to the transversal inclination angle on various types of roads and various turning radiuses.

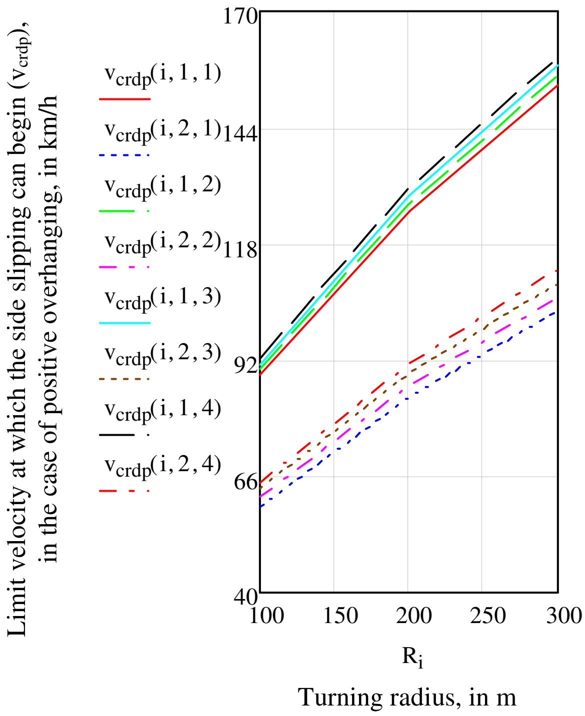

Fig. 12. Velocity variation of the vehicle in turning, at which the vehicle can begin to side slide on a road with transversal inclination with *positive overhanging*, according to the turning radius in the case of various types of roads and various transversal inclination angles.

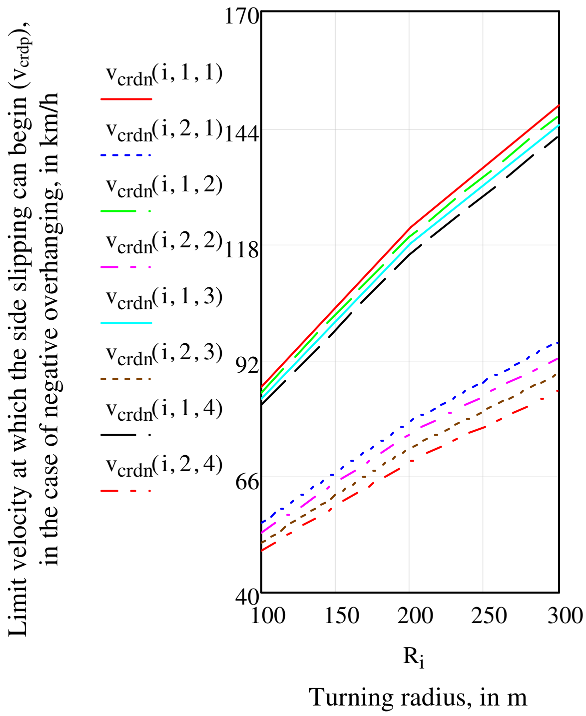

Fig. 13. Velocity variation of the vehicle in turning, at which the vehicle can begin to side slide on a road with transversal inclination with *negative overhanging*, according to the turning radius in the case of various types of roads and various transversal inclination angles.

As a possible development of the present study, we aim to extend the research in order to determine:

– the influence of the vibrations produced by the road on the acceleration and velocity of the vehicle;
– the transversal acceleration of the vehicle on a road with transversal inclination;
– the velocity of the vehicle under other various conditions (various types of roads, various types of loads, etc);
– the transversal stability parameters for various classes of vehicles.

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POSIBILITĂŢI DE EVALUARE A PARAMETRILOR STABILITĂŢII TRANSVERSALE A AUTOVEHICULELOR

Rezumat: Lucrarea surprinde un studiu analitic, prin modelare numerică, privind evaluarea parametrilor stabilităţii transversale a autovehiculelor. La dezvoltarea modelului numeric utilizat s-a ţinut seama de: forțele care acționează asupra autovehiculului aflat viraj; influența poziţiei centrului de greutate al autovehiculului, cât și a greutăţii acestuia, asupra vitezei de deplasare şi a stabilităţii transversale a lui; influența unghiului de înclinare transversală a drumului asupra vitezei de deplasare şi a stabilității autovehiculului; influența razei de viraj asupra vitezei de deplasare și a stabilității autovehiculului. În studiu sunt luate în considerare aspecte referitoare la diferite înclinări transversale ale drumului, diferite raze ale traiectoriei, diferite viteze de deplasare, parametrii principali ai autovehiculului luat în studiu. Rezultatele obținute sunt sub formă grafică și surprind parametrii stabilității transversale a autovehiculului - la răsturnare, prin efectul aderenței transversale, în cazul profilului transversal cu pantă unică şi în cazul profilului transversal cu două versante plane.

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

Nicolae CORDOŞ, PhD. Eng., Lecturer, Technical University of Cluj-Napoca, Faculty of Mechanical Engineering, Department of Automotive Engineering and Transports, Romania, Nicolae.Cordos@auto.utcluj.ro, Office Phone 0264 202 790.

Monica BĂLCĂU, PhD. Eng., Lecturer, Technical University of Cluj-Napoca, Faculty of Mechanical Engineering, Department of Automotive Engineering and Transports, Romania, monica.balcau@auto.utcluj.ro, Office Phone 0264 401 610.