

INFLUENCE OF THE TRACTOR AND SEMITRAILER MASS RATIO ON BRAKING STABILITY

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Semitrailers are frequently used in combination with agricultural tractors for transport systems, due to their smaller constructive weight and total length compared to trailers, and particularly due to their positive influence on transport and braking dynamics [1;4]. This influence is achieved by the contribution to an increase of the tractor adherence load, consequently to the transfer, via the trailer coupling devices, of a part of the semitrailer weight upon the tractor. The semitrailer having only one axle, has as a second supporting point the coupling element of the tractor, located at the inferior part of the tractor rear, below the level of the tractor rear axle.

During the braking process of the tractor – semitrailer combination, the interaction forces occurring in the coupling element between the tractor and the semitrailer can have a negative, even dangerous influence on the stability of the system. The most dangerous phenomenon, frequently noted during operation is the so-called “folding” of the system in the longitudinal plane, which means the lifting of the tractor front axle from the road, a process with direct negative effects on the system manoeuvrability (loss of steering control). Another phenomenon which may occur is the “folding” of the system by sliding – skidding, which means a relative rotation by the joint point in the transversal plane of the longitudinal axes of the tractor and semitrailer, thus generating the so-called “jackknifing” phenomenon, which puts the vehicle completely out of control and often causes considerable damage both to the vehicle itself and to other road users[2, 5].

The lifting process of the front axle and of motion stability loss by sliding – skidding depend directly on the ratio of the semitrailer mass m_s and tractors mass m_t , expressed by the ratio $k_m = m_s/m$ [1, 3]. These considerations call for theoretical research based on dynamic and mathematical models describing the dynamic behaviour of the systems under various braking conditions, as well as for experimental research on the influence of the trailer and tractor mass ratio on the folding phenomenon (by lifting or skidding) during road travelling.

In accordance with the regulations currently in force in Romania, the semi-trailers of a total mass smaller than 6,000 kg (in some countries this limit is higher, e.g. in Germany 8,000 kg) are equipped with inertial control brakes, where the force generated in the semitrailer coupling is transmitted by a mechanical (lever) system to the trailer wheel slippers. Due to its constructive simplicity and reduced cost, this type of braking is widely used in agriculture. Lately the utilisation of inertial control and hydraulic transmission brakes tends to expand, the hydraulic pump being also inertially controlled.

Further on the methods of theoretical research and experimental investigation of the inertial control braking process dynamics of the tractor – semitrailer systems will be presented.

THEORETICAL RESEARCH

The theoretical research is based on the dynamic modelling of the tractor – semitrailer system during the braking process, followed by the development of mathematical models describing the dynamic behaviour of the system under various travelling and braking conditions [3].

In the case of a transport combination(system) including a tractor and semitrailer, the forces shown in figure 1 will be generated in the longitudinal plane. For simplification, the inertial torques of the wheels, the rolling resistance forces and moments of the wheels, as well as the air resistance (due to the small travelling velocities of the tractor – semitrailer system) were neglected. The link between the two elements of the system (tractor and semitrailer) is achieved by a coupling device consisting of the coupling hoop on the semitrailer hitch and the coupling bolt mounted on the tractor hook. The absence of allowances in the trailing point and of elastic links between the tractor and semitrailer will be further assumed.

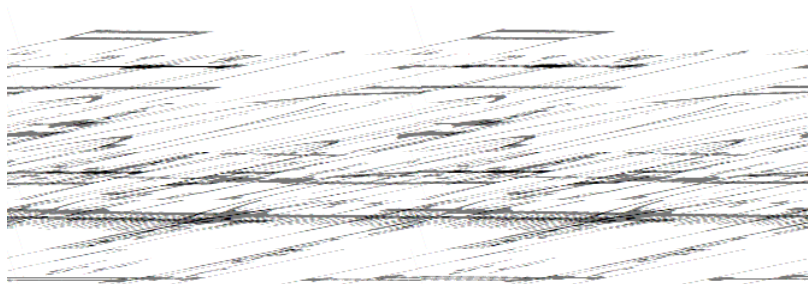


Fig. 1. Forces acting on a tractor – semitrailer system during braking

The dynamic study can be carried out by considering that in the case of braking the system behaves like a vehicle with three axles, the last one being joint coupled to the tractor body. The dynamic analysis of the system is carried out by the isolation method of the component elements of the system, with longitudinal (horizontal) force X_c and vertical force Z_c acting in the coupling device C (fig. 1).

The exterior forces acting upon the system are: G_t and G_s – tractor and semitrailer weights, respectively, applied in their mass centres; F_{it} and F_{is} – the inertial forces of the tractor mass ($F_{it} = (G_t/g)/d$) and of the semitrailer mass ($F_{is} = (G_s/g)/d$) applied in the respective mass centres; F_{b1} , F_{b2} and F_{bs} – the tangential braking forces on the front and rear axles of the tractor and on the axle of the trailer, respectively (generated during the operation of the braking systems of the axles in the wheel – road interface); Z_1 , Z_2 and Z_s – the normal reaction (load) on the tractor and semitrailer axles, respectively.

In literature [3] the ration of the tangential braking forces developed in the axle wheels F_{bs} and the normal loads Z on the respective axles ($\chi = F_b/Z$) represent a specific braking force called *braking force coefficient*. In the case of the three axles these coefficients have the following expressions: $\chi_1 = F_{b1}/Z_1$, $\chi_2 = F_{b2}/Z_2$ and $\chi_s = F_{bs}/Z_s$. Based on Figure 1, the following equilibrium equations are obtained:

a) for the tractor:

$$Z_1 + Z_2 = G_t + Z_c \quad (1)$$

$$\chi_1 Z_1 + \chi_2 Z_2 = G_t d / g + X_c \quad (2)$$

$$(d / g) G_t h_t + X_c h_c + G_t (L_t - a_t + l_c) - Z_2 l_c = Z_1 (L_t + l_c) \quad (3)$$

b) for the semitrailer:

$$Z_c + Z_s = G_s \quad (4)$$

$$X_c + \chi_s Z_s = G_s (d / g) \quad (5)$$

$$G_s a_s + X_c h_c = G_s (d / g) + Z_s L_s \quad (6)$$

c) for the tractor – semitrailer combination (system):

$$Z_1 + Z_2 + Z_s = G_t + G_s \quad (7)$$

$$\chi_1 Z_1 + \chi_2 Z_2 + \chi_s Z_s = (d / g) (G_t + G_s) \quad (8)$$

$$(d / g) G_t h_t + (d / g) G_s h_s + Z_2 L_1 + G_s (L_t + L_s + l_c) = G_t a_t + G_s (L_1 + l_c + a_s) \quad (9)$$

where X_c and Z_c are the horizontal and vertical forces in the coupling device; $d = dv/dt$ – the deceleration during the braking of the system. Other dimensional parameters of the system result from Figure 1.

From the equations presented above, the expressions for the loads on various axles can be expressed by the following:

1) tractor front axle (Z_1):

$$Z_1 = \frac{G_t [L_t - a_t + (d / g) h_t + (\chi_2 - d / g) h_c]}{L_t + (\chi_2 - \chi_1) h_c} + \frac{G_s [L_s - a_s + (\chi_s - d / g) h_c + (d / g) h_s] (\chi_2 h_c - l_c)}{(L_s + \chi_s h_c) [L_t + (\chi_2 - \chi_1) h_c]} \quad (10)$$

2) tractor rear axle (Z_2):

$$Z_2 = \frac{G_t[a_t + (d/g)h_t + (d/g - \chi_1)h_c]}{L_t + (\chi_2 - \chi_1)h_c} + \frac{G_r[(L_s - a_s) + (\chi_s - d/g)h_c + (d/g)h_c][(L_t + l_c) - \chi_2h_c]}{(L_s + \chi_s h_c)[L_t + (\chi_2 - \chi_1)h_c]} \quad (11)$$

3) semitrailer axle (Z_s):

$$Z_s = G_s \frac{[a_s - (h_s - h_c)d/g]}{L_s + \chi_s h_c} \quad (12)$$

It can be observed, that if the deceleration d of the system and the braking force coefficient of the semitrailer χ_s are known, the normal load on the axle of the semitrailer is given by the relationship (12) and the vertical and horizontal loads Z_c and X_c from the coupling device C are given by the relationships (4) and (5), there follows:

$$Z_c = G_s \frac{[(L_s - a_s + \chi_s h_c) + (h_s - h_c)d/g]}{L_s + \chi_s h_c} \quad (13)$$

$$X_c = G_s \frac{[(L_s - \chi_s h_s)d/g - \chi_s a_s]}{L_s + \chi_s h_c} \quad (14)$$

The optimum braking conditions are achieved when in the contact surfaces between wheels and road the same braking force coefficients (χ_1 , χ_2 and χ_s) are reached for all axles, and are equal to the relative deceleration $d/g = \varphi$ (where φ is the coefficient of road adhesion in the braking of the wheels), that is $\chi_1 = \chi_2 = \chi_s = d/g = \varphi$. Consequently, the expressions for the normal loads on the axles and for the forces in the coupling device are given by the simplified relationships;

$$Z_1 = \frac{G_t(L_t - a_t + \varphi h_t)}{L_t} + \frac{G_s(L_s - a_s + \varphi h_s)(\varphi h_c - l_c)}{L_t(L_s + \varphi h_c)}; \quad (15)$$

$$Z_2 = \frac{G_t(L_t - \varphi h_t)}{L_t} + \frac{G_s(L_s - a_s + \varphi h_s)(L_t + l_c - \varphi h_c)}{L_t(L_s + \varphi h_c)}; \quad (16)$$

$$Z_s = \frac{G_s[a_s - \varphi(h_s - h_c)]}{L_s + \varphi h_c}; \quad (17)$$

$$X_c = G_s \frac{(L_s - a_s - \varphi h_s)\varphi}{L_s + \varphi h_c}; \quad (18)$$

$$Z_c = G_s \frac{(L_s - a_s) + \varphi(h_s - h_c)}{L_s + \varphi h_c}. \quad (19)$$

For tractors with brakes only on the rear wheels (the case of rear drive agricultural tractors), the loads on the axles, Z_1 , Z_2 , and Z_s are determined with relationships (10), (11) and (12), and (15), (16) and (17), respectively, where $\chi_1 = 0$.

For determining the interaction force X_C of the coupling device of the semitrailer equipped with the inertial control brakes, the most unfavourable situation for the braking process will be considered, which in practice corresponds to the lagging behind period of the operation of the trailer brakes, equal to the time Δt required by the compensation of the functional allowances in the transmission mechanism of the inertial control brakes. In this situation the maximum value of the longitudinal reaction X_C is given by relationship (14), wherein $\chi_s = 0$, wherefrom follows:

$$X_{c \max} = (d_{\max}/g) G_s \quad (20)$$

where $d_{\max}/g = \varphi_{\max}$ is the maximum adherence coefficient between the wheels of the tractor and the road.

The folding process of the system by the lifting of the front axle starts at the moment at which the load on the front axle is annulled, that is $Z_1 = 0$. Consequently the condition of braking stability is $Z_1 \leq 0$. In reality, in order to ensure the directional control of the system, the international norms foresee $Z_{1\min} = 0.2 G_t$ [1]

Considering the above and introducing the semitrailer and tractor mass ratio, that is $k = m_s/m_t = G_s/G_t$, from relationship (10) the value of the mass ratio k_m can be obtained, marking the beginning of the folding of the system, that is wherefrom the tractor loses its manoeuvrability (by condition $Z_1 = 0$). By introducing into the obtained relationship the concrete values of the characteristic dimensions of a given tractor – semitrailer system, the variation of the minimum mass coefficient k_{\min} is obtained, in dependence on the adherence coefficient φ of the tractor rear axle wheels, wherefrom the values of k_{\min} result for various values of the adherence coefficient φ .

Under the optimum braking condition, the breaking force on the axles are proportional to corresponding normal loads. The required braking force distribution among the axles, therefore, can be determined from the equation (15), (16) and (17). Figure 2 shows the variation of the optimum braking force distribution with coefficient of road adherence φ for a particular tractor-semitrailer under various loading conditions and figure 3 shows the variation of the forces in the coupling device (horizontal force X_c and vertical force Z_c) depending on the coefficient of road adherence φ based on the relations (18) and (19).

The parameters of the tractor-semitrailer system used on the analysis (tractor DT-445 and semitrailer RPI-4, both produced in Romania) are as follows: $G_t = 22450$ N; $G_{s1} = 12500$ N (semitrailer empty); $G_{s2} = 22450$ N (semitrailer partially loaded); $G_{s3} = 52500$ N (semitrailer fully loaded); $L_t = 1.96$ m; $L_s = 4.22$ m; $a_t = 1.22$ m; $h_t = 0.87$ m; $a_s = 3.50$ m; $h_{s1} = 0.70$ m; $h_{s2} = 0.85$ m; $h_{s3} = 1.0$ m; $l_c = 0.3$ m; $h_c = 0.35$ m.

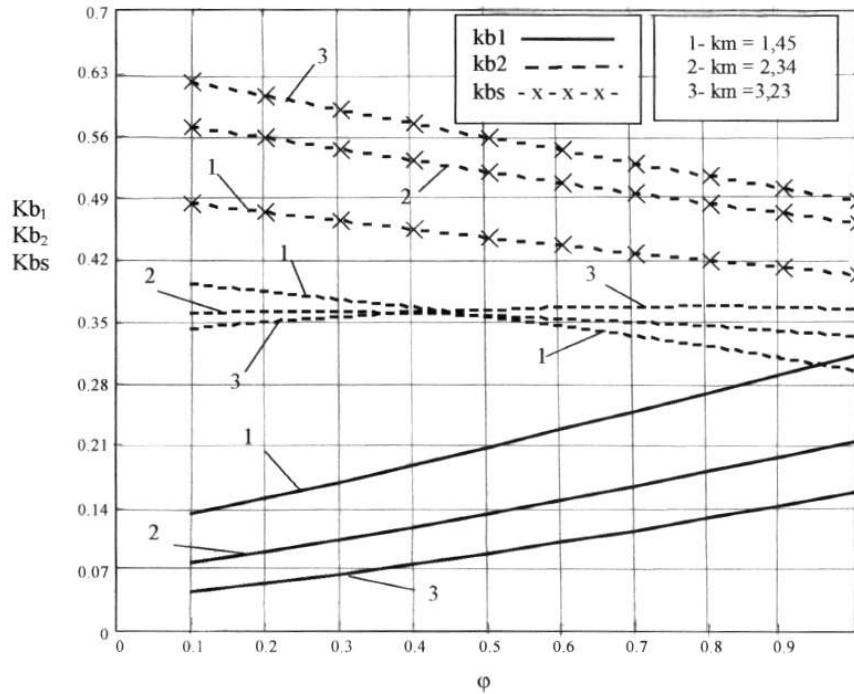


Fig. 2. Variation of ideal braking forces distribution with road adherence coefficient and loading condition for a tractor-semitrailer (DT45+RPI-4)

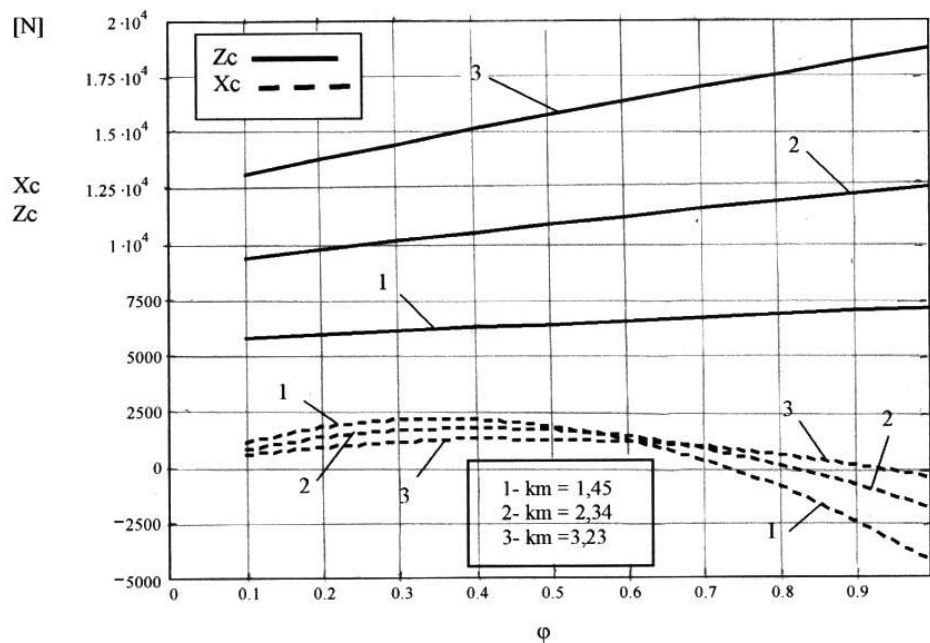


Fig. 3. Variation of the forces in the coupling device (vertical force Z_c and horizontal force X_c) depending on the coefficient of road adherence ϕ

From Figure 2 it can be seen that the optimum value of the braking force distribution on the tractor rear axle $K_{b2} = F_{b2}/(F_{b1}+F_{b2}+F_{bs})$ varies very little over a wide range of road and loading conditions. On the other hand, the optimum value for the braking force distribution on the tractor front axle $K_{b1} = F_{b1}/(F_{b1}+F_{b2}+F_{bs})$ and that on the semitrailer axle $K_{bs} = F_{bs}/(F_{b1}+F_{b2}+F_{bs})$ vary considerably with the coefficient of road adhesion and with the loading conditions of the semitrailer. This indicates that for a tractor – semitrailer combination with a fixed braking force distribution, the optimum braking condition can be achieved only with a particular load configuration over a specific road surface.

Under all other conditions, one of the axles will lock first. As mentioned previously, the locking of tractor front tires in a loss of steering control, the locking of tractor rear tires first results in jack-knifing and the locking of semitrailer tires causes trailer swing. This indicates that the locking sequence of the tires is of particular importance to the behaviour of the tractor-semitrailer during braking. As jack-knifing is the most critical situation, the preferred locking sequence, therefore, appears to be tractor front tires locking up first, then semitrailer tires, and then tractor rear tires. A procedure for predicting the locking sequence of tires of tractor-semitrailers has been developed [1].

REFERENCES

1. **Begheș, H.** Study of the Influence of the Ratio Between the Tractor Mass and the Mass of the Coupled Machine on the Dynamics of Braking and Safety during Displacement in Transport. PhD-Thesis, Transilvania University of Brasov/Romania, 1998.
2. **Mikulcik, E.C.** The Dynamics of Tractor-Semitrailer Vehicles: The Jackkifing Problem. SAE Transactions, vol 80, apper 710045, 1971
3. **Popescu, S., Begheș, H., Demetrescu, I.** Studies and Researches Regarding Determining the Limit Ratio between the Truck Mass and the Tractor Mass from the Point of View of Breaking Stability. Buletinul Conferinței CONAT, Brașov, 1996, vol.2, p.335-342.
4. **Popescu, S., Begheș, H., Popa, L.** Contribuții la studiul stabilității la frânare a sistemelor de transport tractor-semiremorca. Buletinul ISBTech-București 2002, p. 64-67.
5. **Wang, J.Y.** Theory of ground vehicle, John Wiley and Sons, New York, 1993.

SUMMARY

The paper presents a theoretical research method of the dynamic behaviour in the braking of tractor – semitrailer transport combination. Based on the equivalent dynamic model of the real physical system, the mathematical model describing the dynamic behaviour of the system during braking is developed, thus allowing computer simulation of the dynamic behaviour of the system and its components (tractor and semitrailer). The experimental investigation has highlighted a good agreement of the results obtained theoretically (computer aided simulation) and experimentally (by measurements) regarding the dynamic parameters of the braking process.