INFLUENCE OF THE CONSTRUCTION OF CAR BRAKES ON ITS STABILITY DURING BRAKING

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Abstract. In the Paper, stability of a car during its braking is analyzed. In the theory of vehicles, stability is considered an ability of a vehicle to follow the certain set trajectory without any vehicle-controlling actions of the driver. In the Paper, the importance of the structural elements of a car (such as the anti-lock braking system and the regulator of braking forces), its technical condition, and the interwheel differential for its stability on braking is discussed upon. Herein, the above-mentioned mode of movement of a car is described by analytic formulas and graphical dependences. Conclusions and proposals are provided.

Keywords: vehicle, braking, stability, regulator of braking forces, ABS, differential.

1. The Introduction

Stability is an ability of operating equipment, system or phenomenon to keep the own parameters. Stability of movement of a vehicle is understood as its ability to follow the set trajectory without any vehicle-controlling actions of the driver. Hereinafter, some principal definitions usable to describe movement of a vehicle are provided.

Trajectory is a line showing the way of movement of the vehicle. Trajectory-based control is control of a vehicle upon preserving or changing the trajectory of its movement. Trajectory-based losing stability usually is assessed by the value showing the deviation of the vehicle from the set passageway that conforms to the width of the lane according to the Technical Road Regulation KTR 1.01:2008 [1].

Course – the direction of movement of the vehicle described by the velocity vector. Course-based control is control of a vehicle in respect of the longitudinal axis. A deviation from the chosen course is assessed by the angle between the chosen course and the longitudinal axis of the real movement of the vehicle. The less the said angle the better course-based stability is.

The braking distance $S_{st}$ is the distance covered by the vehicle on its braking. The beginning of braking is considered the moment of pushing the braking pedal. The stopping distance $S_0$ is the braking distance plus the distance covered by the car during the time of the driver’s reaction $t_r$.

Braking modes include extreme braking, i.e. braking upon striving to the maximum possible speed of braking (the goal: to stop the vehicle as rapidly as possible); emergency braking, i.e. the same, as the extreme one, but striving to avoid a traffic accident; and service braking, i.e. braking with low acceleration $a$ (in this case, $a < 3 \text{ m/s}^2$).

The causes of instability of a car on its braking can include different braking forces that affect the left and the right wheels, different coefficients of adherence of tyres with the surface of the road, external forces (including controlling actions of the driver), and locking of wheels.

Some of the above-listed factors are predetermined by the structure of the braking system of the vehicle.

In the Paper, the impact of the structure of the braking system of a car upon its stability on braking is discussed upon.

2. The theoretical dependence of movement of a car on its braking and the causes of losing its stability

On examining the movement of a car on its braking, let’s use the theoretical dependence of acceleration of braking on time $a = f(t)$ [2–4] (Fig. 1), upon a disregard for any resistance forces. In the diagram, $t_2$ is the time interval between the moment of activation of the braking mechanism and the moment of beginning of braking of the car (for hydraulic brakes $t_2 = 0.05–0.1 \text{ s}$); $t_3$ is the time of growing of the acceleration of braking approximately equal to $0.05–0.6 \text{ s}$ (directly proportional to the coefficient of adherence of tyres with the surface of...
the road $\varphi$ and the mass of the car $m$; $t_d$ – the time of movement with released brakes (is very short, so is neglected); $a_s$ – the settled accelerations of braking. The time of the driver’s reaction $t_1$ (not shown in Fig. 1) can be equal to $0.2–1.5$ s; usually, the value of $0.8$ s is accepted.

If we suppose that deceleration grows from 0 to $a_s$ within the time interval $0.5t_d$ (Fig. 1), $S_{st}$ is found from the area under the curve $v = f(t)$. Upon such a supposition, the said area is some larger than the one obtained on precise calculation; however, the difference is negligible:

$$S_{st} = v_0(t_2 + 0.5t_d) + 0.5v_0(0.5t_d + t_s), \quad (1)$$

where $v_0$ – the initial velocity of the car.

Because $0.5t_d + t_s = v_0/a_s$, the values of $S_{st}$ and $S_0$, when $a_{n, max} = g \varphi$ (where $g$ – gravitational acceleration) and the final velocity $v = 0$, will be found as follows:

$$S_{st} = v_0(t_2 + 0.5t_d) + v_0^2/(2g \cdot \varphi), \quad (2)$$

$$S_0 = S_{st} + v_0 \cdot t_1. \quad (3)$$

So, the length of the stopping distance, if the resistance forces are not taken into account, will be approximately proportional to the initial velocity of movement of the vehicle and inversely proportional to the coefficient of adherence of tyres with the surface of the road.

As it was mentioned above, losing stability on braking can be caused by different braking forces that affect the left and the right wheels, different coefficients of adherence of tyres with the surface of the road, external forces, and locking of wheels.

Different forces affecting the left and the right wheels of the vehicle (upon a good condition of the system of service brakes) can be caused by wear and tear of the brake shoes or accumulation of mud, lubricant or moisture on the friction-affected surface.

Locking of wheels on braking when the vehicle still is moving suddenly decreases the value of the coefficient $\varphi_i$ of adherence of tyres with the surface of the road the vehicle is moving on in the cross direction that, in its turn, causes a decrease of resistance of tyres to side forces.

Usually, the vertical reactions $R_l$ of the front and the rear wheels of standing fully loaded car to the surface of the road ($R_l$ or $R_r$, respectively) are distributed 50% for each, i.e. $R_l/R_r = 1$. On braking, their redistribution takes place: the reaction of the front wheels is increasing and the reaction of the rear wheels is decreasing. The maximum braking force affecting wheels of each axle $F_{st, max} = \varphi_i R_i$.

The optimum distribution of braking forces and the maximum efficiency of braking are achieved upon the same maximum braking forces of all wheels. Usually, the distribution of braking forces between the wheels of the front and the rear axles is expressed by the coefficient of distribution of braking forces $\beta_1$ equal to the ratio of the braking force that affects the wheels of the front axle with the braking force that affects the wheels of the rear axle (it is supposed that the forces of resistance to movement equal to zero and $a_{n, max} = \varphi_i g$).

In absence of a regulator of braking forces in the system of brakes, the optimum distribution of the braking forces in the system of brakes takes place only in a case, when $\varphi = \varphi_0$ (where $\varphi_0$ – the coefficient of adherence of tyres with the surface of the road when the wheels of the both axles are locked simultaneously). When $\varphi < \varphi_0$, the front wheels are locked first; when $\varphi > \varphi_0$, the rear are locked first. The second case is more dangerous. Because of this, the Annex 10 of the UN EEC Regulation No 13 [5] recommends to choose such a distribution of the braking forces in the system of brakes of cars without a regulator of braking forces that ensures $\varphi_0 \geq 0.7$.

The front wheels are locked prior to the rear ones when $\varphi < \varphi_0$. In such a case, the maximum braking force is not achieved at the rear wheels when the front wheels achieve locking already and the coefficient $\varphi_i$ of adherence in the side direction decreases suddenly. This circumstance predetermines losing of stability on braking and sliding of the front wheels (the controllability is lost). However, the driver can feel such losing of controllability from the very beginning and avoid it by decreasing the force of pressing the braking pedal.

The rear wheels are locked prior to the front ones when $\varphi > \varphi_0$. In such a case, the maximum braking force is not achieved at the front wheels when the rear wheels achieve locking already and the coefficient $\varphi_i$ of adherence in the side direction decreases suddenly. This circumstance predetermines losing of stability on braking and sliding of the rear wheels, so controllability of the vehicle is lost. In such a case, the driver can feel such losing of controllability from the very beginning; however, the
The driver cannot avoid it by decreasing the force of pressing the braking pedal. Because of this, lockage of the rear wheels is considered more dangerous than lockage of the front wheels.

3. The impact of the structure of the braking system upon stability of the vehicle on its braking

For vehicles equipped with a regulator of braking forces, a considerably less value of $q_0$ is recommended. For example, for fully loaded five-seat car, $l_1/L = 0.5$, $h/L = 0.37$ ($L$ – the length of the car; $l_1$, $h$ – the distances between the center of gravity and the front axle and the surface of the road, respectively). In such a case, $q_0 = 0.42$ and $\beta_{st} = 1.275$. If the load of the car is 20% (a car with a driver), these parameters will be $q_0 = 0.22$ and $\beta_{st} = 1.34$. For a real vehicle:

$$F_{st1} = C_1(p_1 - p'_1) \quad \text{and} \quad F_{st2} = C_2(p_2 - p'_2),$$

where $C_1$ and $C_2$ – the structure-related constants, $p'_1$ and $p'_2$ – pressures proportional to the forces of the return springs. In addition, for a real vehicle without a regulator of braking forces, $p_2 = p_1$.

In Fig. 2, the ideal dependences $p_2 = f(p_1)$ (the dotted lines) are shown. In this case, the maximum braking forces are achieved when the dependences of $p_2$ and $p_1$ on $p$ are nonlinear and – taking into account the load of the vehicle – different.

![Fig. 2. The optimum distribution of braking forces](image)

A dynamic regulator of braking forces changes the pressure $p_2$ dependently on the force of pressing the brake’s pedal and the vertical reaction of the rear wheels. Such regulators regulate $p_2$ dependently on $p_1$ (the broken curves 0-a-c and 0-b-d).

Hereinafter, the scheme and the principles of operation of such a regulator are discussed upon. Its case with the piston 1 (Fig. 3) and the valve 2 is fixed to the body of the vehicle. Through the lever 4 with the regulating screw 3, the piston is affected by the torsion’s force $F_{tor}$. The other end of the torsion is connected with the rear axle by the rods 6 and 7. The piston is affected by the force $F_{sp}$ of the spring 8 as well.

![Fig. 3. The scheme of a regulator of braking forces: 1 – the piston; 2 – the valve; 3 – the regulating screw; 4 – the lever; 5 – the torsion; 6, 7 – the rods; 8 – the spring; $p$ – pressure; $F$ – force; $R$ – the reaction of the road to the wheels](image)

The system for regulating the pressure $p_2$ dependently of the pressure $p_1$ and the reaction $R_{zu}$ expressed by the deflection of the suspension $f$ consists of three elements: the rear suspension of the vehicle – the torsion – the regulator. The equations of the regulator’s controlling are following:

$$p_2 = p_1, \quad \text{if} \quad p_1 \leq p_0$$

$$p_2 = [F_{tor} + F_{sp} + p_1(A_2 - A_1)]/A_2, \quad \text{if} \quad p_1 > p_0,$$

where $F_{tor}$ – the torsion’s force, $F_{sp}$ – the spring’s force, $A_1$ and $A_2$ – the areas of the surfaces of the pistons in the wheel braking cylinder and in the regulator of braking forces, respectively.

The linear equations of the static balance of the vehicle and the rear suspension will be following:

$$R_{zu} = [m \cdot g \cdot h_1 - h(F_{st\,p} + F_{st\,u})]/L;$$

$$R_{zu} = R_{zu\,0} + c_p(f - f_0),$$

where $f$ – the deflection of the suspension, $c_p$ – the coefficient of stiffness of the suspension. After certain mathematical operations with (5) and (6), when $p_1 > p_0$, the dependence $p_2 = kp_1 + b$ is found (where $k$ and $b$ – real numbers). This equation is the equation of the straight for the segments a-c and b-d (Fig. 2).

For assessing the efficiency of operation of a regulator, the coefficient of weight utilization $m_c$ is usable: taking into account the total mass of the vehicle, it shows how many times the braking force upon using the braking system with a regulator of braking forces is less as compared to the one upon the optimum distribution of braking forces. In this case, we find that:
In Fig. 4, the dependence of the said coefficient on the coefficient of adherence is shown (the dotted curves – with a dynamic regulator, the continuous curves – without it, the bold curves – 100% load, the thin curves – 20% load). As the Fig. 4 shows, a regulator of braking forces increases considerably the coefficient \( m_\varepsilon \) and the value of the latter approaches to one; however, this phenomenon takes place only in the zone where \( \varphi > \varphi_0 \) (\( \varphi_0 \) values conform to the points \( c \) and \( d \), Fig. 4). However, even upon \( \varphi < \varphi_0 \), using a regulator of braking forces is desirable, because \( \varphi_0 \) becomes about 1.5 times less as compared to a braking system without a regulator of braking forces.

![Fig. 4](image)

**Fig. 4.** The dependence of the coefficient of weight utilization \( m_\varepsilon \) on the coefficient of adherence of tyres with the surface of the road \( \varphi \)

It is notable that a regulator of braking forces is a rather simple mechanism, free of any electronic parts, pumps, reservoirs and so on. It can be installed in any system of brakes, such as hydraulic or pneumatic with one, two or more contours. In case of service braking, vehicles with and without a regulator of braking forces are of equal value in respect of their braking properties. In case of extreme braking, the braking distance of vehicles with a regulator of braking forces is less than this distance for vehicles without a regulator of braking forces for all values of \( \varphi \), except of \( \varphi_0 \) for a vehicle without a regulator of braking forces. However, a regulator of braking forces does not eliminate a locking of wheels; it allows simultaneous locking of the front and the rear wheels only. Nevertheless, a regulator of braking forces reduces a risk of instability on braking.

**Anti-lock braking system (ABS)** automatically reduces an excess of the braking moment \( M_\varepsilon \) (the product of the braking force in the zone of the contact between the surface of the road and the tyre and the radius of the wheel), prevents locking of the wheels and enables braking by all wheels up to their sliding limit. Among various ABSs, the systems regulating the value of the braking moment are considered the most effective. Such ABSs [6] enable to preserve average sliding of wheels close to the value of \( \lambda_0 \) when the coefficient of adherence \( \varphi = \varphi_{\text{max}} \).

In Fig. 5, the principle of operation of one of ABSs is shown. In course of its growing, the braking force of the rear wheels \( F_{\text{st}} \) exceeded the value of \( F_{\varphi_{\text{max}}} \) in the point \( a \). The angular velocity of the rear wheels \( \omega_p \) began reducing as compared to the velocity of the non-locked front wheels \( \omega_u \). In the point \( b \), the difference \( \omega_p - \omega_u \) achieved the value \( \Delta u \) fixed by the slipping assessment block (SAB) in the electronic control system. From SAB, the signal is transmitted to a modulator for processing values of the braking moment; the latter is activated with the delay of \( \tau \) (the point \( c \)) and starts reducing \( M_\varepsilon \).

![Fig. 5](image)

**Fig. 5.** The dependence of the braking force \( F_\varepsilon \) and the angular velocity of wheels on time \( t \)

In the point \( d \), \( \omega_p \) further reduces, because upon the wheels’ sliding \( \lambda > \lambda_0 \), the value of \( \varphi < \varphi_{\text{max}} \) and only in the point \( e' \), \( F_{\text{st}} = F_{\varphi} \) and deceleration of the wheels ceases, i.e. \( \omega_p/\alpha = 0 \). It is fixed by the control system and the latter sends a signal to the modulator. From the point \( e' \), the locked wheels start running-out, because \( F_{\text{st}} < F_{\varphi} \). In the point \( e \), the modulator ceases reducing the braking moment.

In the point \( f' \), the difference \( \omega_p - \omega_u \) becomes equal to \( \Delta u \), so SAB sends a signal to the modulator and the latter is activated with a delay equal to \( \tau' \) (the point \( f \)). In the point \( g \), \( \omega_p = \omega_u \) and \( F_{\text{st}} = F_{\varphi_{\text{max}}} \) again, as in the point \( a \). However, \( F_{\varphi} \) is increasing, so \( \omega_u \) begins reducing. The described cycle usually repeats with 6–12 Hz frequency.

The indicator of efficiency of ABS usually is considered the degree \( q \) of using the maximum value of the coefficient of adherence \( \varphi_{\text{max}} \) – it achieves 0.8. In such a case, the braking distance on a slippery road reduces by 10–15%.

It should be noted that the scheme of ABS is rather complicated (it includes electronic parts) and the hydraulic braking system requires pumps, reservoirs and so on (Fig. 6). In addition, individual contours with controllable pressure are needed for the braking mechanism of each wheel. Simple ABSs, including mechanical ones (without electronic parts) are being developed as well. In fact, a benefit of ABS
is felt on a slippery road; if the road is dry, the benefit can remain unperceived. However, on any road, ABS causes increasing of stability of the vehicle; this system is particularly important for road trains.

\[ M_{st,dif,d} = M_{0,dif} (1 + K) \]

If braking is performed by service brakes, when the right and the left driven wheels are not disconnected from the engine, their braking forces will differ; in such a case, an interwheel differential helps to maintain transverse stability of the vehicle by reducing the difference between the braking forces of the right and the left wheels.

Let’s suppose that the braking moment transferred by the braking mechanism to a left driven wheel exceeds the braking moments transferred to the right wheel \((M_{st,mk} > M_{st,mk})\). So, rotation of the left wheel becomes slower than rotation of the right one. Because the disconnected engine takes part in the braking process as well, it transfers braking moment to driven wheels and the driven wheels transfer braking moment to it. Because of this, the part of braking moment of the left wheel transferred via the differential \(M_{st,dif,k} > M_{0,dif} (1 - K)\) (\(K\) – the coefficient of efficiency of braking) will be less that the part of the braking moment of the right wheel transferred via the differential \(M_{st,dif,r} = M_{0,dif} (1 + K)\). So, the moment of rotation of the left wheel \(M_{st,k} = M_{st,mk} + M_{st,dif,k}\) will be less than the moment of rotation of the right wheel \(M_{st,r} = M_{st,mr} + M_{st,dif,r}\) by the value \(2M_{0,dif}K\). If braking is carried out by the engine only, the differential equalizes the velocities of both driven wheels.

4. Conclusions and proposals

1. A stability of a car on its braking, when the value of the coefficient of adherence of the tyre with the surface of the road in the cross direction falls dramatically, is predetermined by external forces (wind), the environment of the road, the actions of the driver as well as the condition and the structure of the braking system. Two last factors are the most important.

2. A regulator of braking forces does not eliminate locking of wheels; it allows simultaneous locking of the front and the rear wheels only. This factor reduces a risk of instability on braking.

3. ABS prevents locking of wheels of vehicle on its braking (locking of wheels is the principal cause of losing stability of a vehicle on its braking), so the value of the coefficient of adherence with the surface of road remains large in the cross direction and a probability of appearance of instability reduces.

4. If braking of a vehicle is performed by the engine, the interwheel differential equalizes the velocities of both driven wheels and helps to maintain transverse stability of the vehicle.

5. Striving to avoid losing stability in a easier way, it is recommended to improve preparation of future drivers for practical driving and to urge involving of manufacturers of vehicles in development of updated braking systems (with ABS and others) in order to avoid the undesirable locking of the rear wheels – the principal cause of losing stability.

References


