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Original Scientific Paper

MALFUNCTION OF THE BRAKING FORCE REGULATORS IN MOTOR VEHICLES AS A POTENTIAL CAUSE FOR TRAFFIC ACCIDENTS

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Abstract

The braking systems in motor vehicles are one of the most important factors of active safety. Malfunction of particular elements that leads to incomplete function or sheer breakdown of the braking system, is the cause of a significant number of traffic accidents. The braking system regulation plays a significant role in the process of efficient braking by using the existing adhesion of the wheels and the substrate, and by maintaining the stability and manageability of the vehicle in the process of braking; all of that while creating the shortest possible braking path.

With the intent of contributing to the development of road traffic safety, the authors of this paper will elaborate on the necessity of the braking system regulation that is generated by the wheels of road motor vehicles; braking force regulators and their types; the necessity for their maintenance; and their immense influence on the braking efficiency and therefore traffic safety in general. This, in combination with the knowledge of characteristic braking trails, can contribute to the quality of evidence assessment in traffic accidents, as well as the quality of vehicle inspection procedures.

Basically, the purpose behind this paper captures braking forces regulation of 2 axle vehicles as well as heavy goods vehicles, including a combination of vehicles (towing vehicle – coupling vehicles) also. In order to emphasize the seriousness of this problem, this paper also includes one specific example of a traffic accident, with emphasis on the probable cause of the accident.

Keywords: Vehicle, braking system, adhesion coefficient, stability, manageability, braking force regulators

I. Introduction

The braking system represents an important factor in traffic safety, and it can be said that it is one of the most important systems that have their own large contribution to the segment of active safety among motor vehicles. The braking regimes may be divided into:

- Abrupt braking, used in sudden situations, so in this case, the timing and way of braking should be as short as they can be,
- Gradual-light braking, used in cases of planned slowing down, or stopping the vehicle,
- Light long-lasting braking, used in movements in large downhill slopes, a regime of work that is especially characteristic of trucks,
- Permanent braking of the vehicle in place.

In any one of the aforementioned braking regimes, contemporary braking systems should satisfy a large number of demands that, in interest to this paper, are the following:

- Rise in the braking moment of every wheel proportionally to the normal reactions of the wheel (or by axes), respectively to the tangent reactions of every wheel,
- Stability and manageability of the vehicle in all braking regimes, without various deviations and others,
- Opportunity for regulating or automatic self-regulating of the braking force against tangential (normal) reactions of the front and back wheels.

II. Theoretical Settings of Braking, Stability, and Engineering Research

II.1. Braking wheel theory

During the vehicle's wheel braking, a revolving moment comes about in a different direction than its direction of turning (moment of braking). In the contact of the wheel and the substrate, a tangent reaction develops, in an opposite direction than that of the direction of movement of the vehicle (braking force). This force opposes the force of inertia or some other propulsive force that moves the vehicle (e.g. downward hill). The braking moment brought onto the wheel is done so with a brake or a retarder.

The forces and moments that act on the braking wheel (figure 1) are the following:

$G = g \cdot m_t$ - normal loading of the wheel caused by the mass coming off of the wheel m_t

F_a- inertial force,

M_{ok}- moment of propulsion that acts over the course of the braking,

M_k- moment of braking that is realized in the brake or retarder,

M_{ft}- moment of resistance of turning of the wheel

From the moment equation of balance of a braking wheel (figure 1), the tangential reaction is:

$$X_k \cdot r_d + M_{ok} - M_{ft} - M_k = 0$$

$$X_k = \frac{M_k + M_{ft} - M_{ok}}{r_d}$$

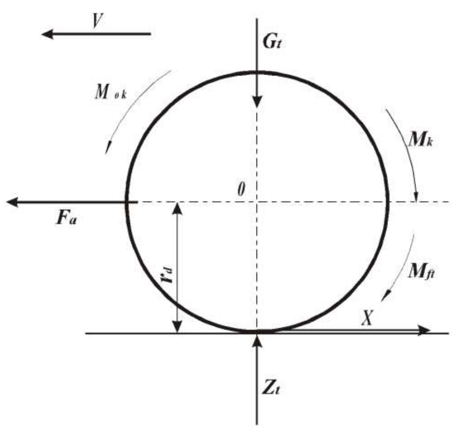

Figure 1. Forces acting on a braking wheel

The tangential reactive force represents the total braking force which slows the vehicle down. The propulsive moment that acts on the wheel during the course of the braking is usually neglected (the performances of the braking system are observed with a disconnected clutch), so in this case, the tangential reactive force can be shown in the form of:

$$X_k = F_k + R_{ft}$$

Here, labelled with F_k, is the generated force in the brakes, i.e. $F_k = \frac{M_k}{r_d}$.

The brake develops the braking moment M_k, that is, the force $F_k$is an imagined vast force on the wheel that has the same effect as the moment M_k. So, if for the given movement conditions, that is, for a given value of resistance of rolling R_{ft}, it is needed to accomplish a braking force of X_k, so the brake of the wheel should reach a final braking moment:

$$M_k = \left(X_k - R_{ft}\right) \cdot r_d$$

In a wheel that brakes on a hard substrate - which is the most common case, and that, from the aspect of traffic safety, is most important, the rolling resistance has small, i.e. negligible values, so the previous expression can be brought down to:

$$M_k = X_k \cdot r_d \cong F_k \cdot r_d$$

with which, from a traffic safety perspective, a degree of certainty is reached.

The maximal braking force value that is reached in wheel-substrate contact, is limited with the conditions of this contract. For the scheme of the braking wheel in figure 1, which is loaded with mass that causes normal loading $g \cdot m_t$, that is, a normal reactive force Z_t, the tangential reaction has a value:

$$X_k = \varphi_m \cdot Z_t,$$

in which, $\varphi_m$is the greatest value of adhesion between the wheel and substrate. In this way, the defined adhesion represents a measure of the quality of contact between the wheel and substrate, that is, the relation between the normal and maximal tangential reactive force of the wheel. Because of that, the maximal value of the adhesion is also called a coefficient of adhesion, which often, for simplicity purposes, is just marked as φ, i.e. $\varphi_m = \varphi$.

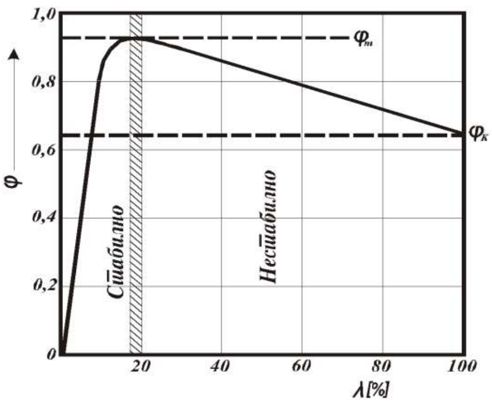

Figure 2. Correlation between adhesion and slipping

Since the braking force also depends on the braking torque applied, each of its values is less than the maximum possible in terms of the maximum adhesion, ie. for each $X_k < X_{kmax}$, the following relationship applies:

$$X_k = \varphi_s \cdot Z_t$$

where φ_s marks the so called used adhesion, in which $\varphi_s < \varphi$ always applies.

The adhesion between the wheel and the substrate is a very complex phenomenon that can be interpreted through the adhesion coefficient only with large simplifications, i.e. in a manner of self-orientation. Adhesion is not a constant or a coefficient, but a process that depends on many factors, and above all on the slip of the wheels λ. Unlike a propulsion wheel, which reaches the adhesion boundary angularly (sliding in place), the brake wheel locks and slips translationally. The size of the slip depends on the adhesion applied, and thus the size of the braking force. Figure. 2 show a typical form of slip adhesion dependence, called the adhesion curve. As can be seen in the figure, the adhesion initially increases relatively rapidly with the increase of the slip and reaches its maximum at relatively low values of said slip $\varphi_m = \varphi$. These slip values are usually 10-20%. Upon reaching the maximum, the adhesion decreases slightly with the further increase of the slip, so that when sliding 100%, i.e. when locking the wheel, the adhesion reaches the value of $\varphi_k$which is significantly lower than the maximum $\varphi_k < \varphi_m$. Adhesion while fully locking the wheel, i.e. during its traslatoral sliding on a substrate is basically a phenomenon that is very similar to friction during sliding between the pneumatic and substrate.

II.2. Utilizing the available adhesion

The maximum values of deceleration, and thus the minimum values of the time and the braking path, can be achieved only if the full adhesion of all the wheels of the vehicle is fully utilized. The maximum adhesion values are close to one, so the maximum deceleration can theoretically reach values close to or at least comparable to the *acceleration of the earth's gravity*. Because of this, and for practical reasons, the evaluation of the braking properties of a vehicle is usually related to the relative relationship between deceleration and gravity, i.e. with the so-called *coefficient of braking* (*brake coefficient*):

$$q = \frac{a}{g}$$

The braking coefficient is a kind of measure of taking advantage of the available deceleration possibilities which could theoretically be at the level of the Earth's acceleration. On this basis, requirements are also defined in a multitude of regulations relating to the performance of brake systems, such as technical inspection regulations. The term brake coefficient is also widely used in the ***ECE-13*** rulebook, as well as in other homologation regulations in this area. The templates for utilizing the two-axle grip available, as well as a combination of towing vehicle - trailer or semi-trailer (trailer train), are provided below.

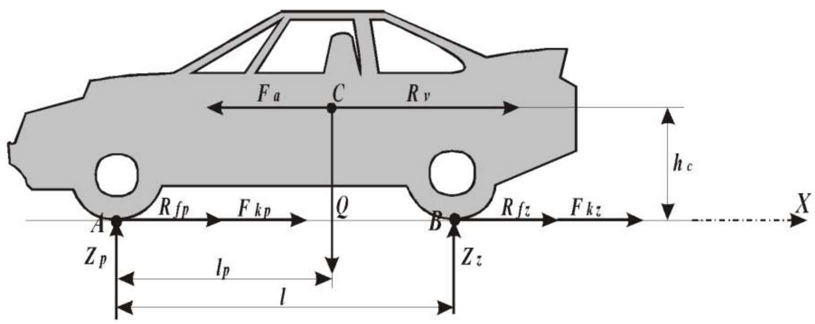

Figure 4. Forces that impact a two-axle vehicle

__Two-axle vehicle:__

for the two-axle vehicle in Figure 3, using conditions of balance

$$\sum M_B = 0 \qquad Z_p \cdot l - Q \cdot l_Z - F_a \cdot h_C + R_V \cdot h_C = 0$$

$$\sum M_A = 0 \qquad Z_p \cdot l - Q \cdot l_p + F_a \cdot h_C - R_V \cdot h_C = 0$$

$$\sum Y = 0 \qquad Z_p + Z_Z - Q = 0$$

When neglecting air resistance $R_V \approx 0$, and using the relations$Q = g \cdot m$ and the braking coefficient $q = \frac{a}{g}$, the following relations can be established:

$$\frac{F_{kp}}{m \cdot g} = \frac{F_{kp}}{Z_p} \cdot \frac{Z_p}{m \cdot g} = \varphi_{sp}\left(\frac{l_z + h_C \cdot q}{l}\right)$$

$$\frac{F_{kZ}}{m \cdot g} = \frac{F_{kz}}{Z_z} \cdot \frac{Z_z}{m \cdot g} = \varphi_{sz}\left(\frac{l_p - h_C \cdot q}{l}\right)$$

From the conditions of balance, we get:

$Z_p = m \cdot g \cdot \frac{l_z + h_C \cdot q}{l}$, $Z_z = m \cdot g \cdot \frac{l_p - h_C \cdot q}{l}$

Thus, the actual deceleration, that is, the actual brake coefficient of the vehicle for utilizing the available adhesion is:

$$q = \varphi_{sp} \cdot \frac{Z_p}{m \cdot g} + \varphi_{sz} \cdot \frac{Z_z}{m \cdot g} +$$

The maximum deceleration can only be achieved if it is $\varphi_{sp} = \varphi_{sz} = \varphi$, if the available adhesion is fully utilized on all wheels. In other cases, when $\varphi_{sp} < \varphi$or $\varphi_{sz} < \varphi$, the deceleration will be less and the braking path longer than theoretically possible values. Similarly to the use of the available grip on other vehicle configurations, for a semi-trailer towing train (Figure 4), the use of the available grip will be:

Combination of towing semi-trailer vehicles:

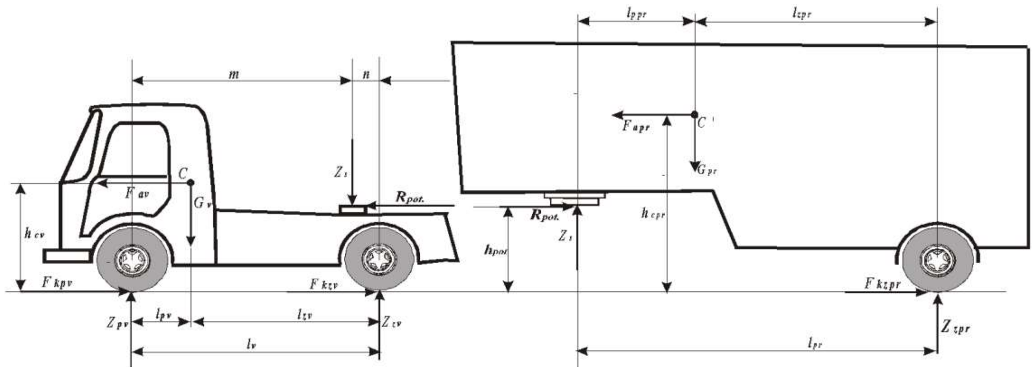

Figure 4. Forces that impact a semi-trailer towing train

The brake coefficient of the towing train, in the function of the degree of utilization of the available adhesion, when brakes are put on all the wheels are can be expressed as with a two-axle vehicle with a single-axle trailer, that is:

$$q = \varphi_{spv} \cdot \frac{Z_{pv}}{G_{vv}} + \varphi_{szv} \cdot \frac{Z_{zv}}{G_{vv}} + \varphi_{spr} \cdot \frac{Z_{pr}}{G_{vv}}$$

The maximum deceleration can only be achieved if it is $\varphi_{spv} = \varphi_{szv} = \varphi_{spp} = \varphi$, if the available grip on all wheels of the vehicle combination is fully utilized. In the other cases, when $\varphi_{spv} < \varphi$, $\varphi_{s\text{B}v} < \varphi$ or $\varphi_{spr} < \varphi$, the deceleration will be smaller and the braking path longer than theoretically possible values.

II.3. Vehicle stability while braking

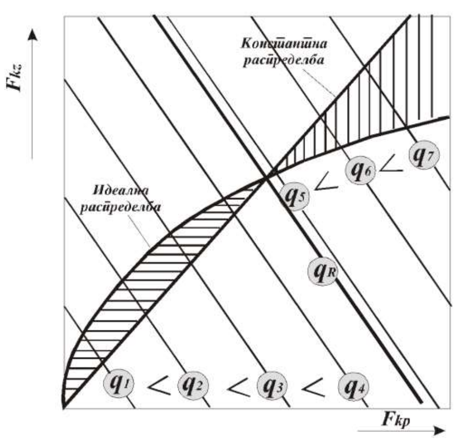

Figure 5. Ideal and constant distribution of brake forces at two-axle vehicles

As important as it is for the vehicle to stop as soon as possible in the event of danger, it is equally important that during braking it does not lose its stability and steering, i.e. it follows the trajectory dictated by the driver. However, during heavy and abrupt brakes the vehicle becomes very unstable, which can cause severe and unintended consequences.

In a two-axle vehicle, the vehicle becomes unstable if the braking is made at the adhesion limit of one or both axles of the vehicle. In such a case the wheels are locked and they are transplatorally sliding onto the road surface. Locked wheels are unable to provide cornering reactions to any external disturbance, making vehicles whose wheels are locked unstable, so external disturbing forces (lateral wind, centrifugal force, etc.) may displace, or "eject" it from the desired trajectory of movement.

For a vehicle to be stable during braking, i.e. when the brakes do not lock the wheels on any axe, the two-axle vehicle stability condition, with normal reactions of the front and rear bridgesZ_p и $Z_z$on the road surface with a coefficient of braking adhesion, can be expressed as follows.

$$\frac{F_{kp}}{F_{kZ}} = \frac{Z_p \cdot \varphi_p}{Z_z \cdot \varphi_z}$$

In which: $F_{kp} \approx X_{kp}$ i $F_{kz} \approx X_{kz}$respective braking forces (with neglecting the rolling resistance).

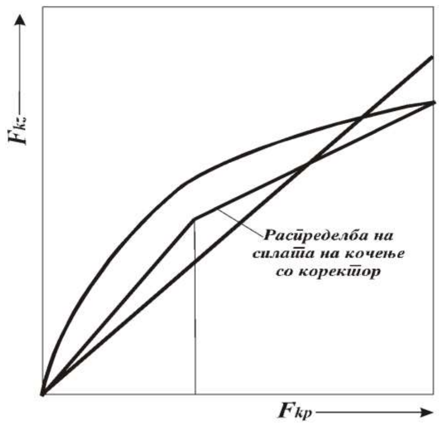

Figure 6. Distribution of brake forces at a two-axle vehicle with a corrector

The ideal and constant distribution of brake forces between the axles of a two-axle vehicle is shown in the diagram in Figure 5. The diagram of Figure 5 can also illustrate the order of vehicle axle locking in a constant brake force distribution system. For all decelerations smaller than $q_r(q_1, q_2, \ldots\ldots)$the front wheels will first be locked (rear wheel braking force is less than the ideal distribution). For all slowdowns greater than qr (q5, q6,… ..) the rear axle wheels will first be locked (then the rear axle braking forces are significantly larger than needed in the ideal distribution). For all slowdowns greater than $q_r(q_5, q_6, \ldots\ldots)$ the rear axle wheels will first be locked (then the rear axle braking forces are significantly larger than needed in the ideal distribution).

II.4. Braking forces regulation

The brake force regulators towards the rear axle of two-axle vehicles have the task of approximating the braking force distribution feature to the ideal distribution (Figure 6). There are different types of adjustments, but in the case of vehicles, regulators are often used to limit the pressure on the rear brakes, i.e. the brake forces on the rear wheels depending on the load on the rear axle of the vehicle, expressed through the bending of the elastic elements or otherwise convenient ways. In heavy truck vehicles with a pneumatic braking system, the tire braking force is often used to regulate the braking forces towards the rear axle of the vehicle through a so-called ASR device (a device for automatic regulation of braking forces). The appearance of an ASR device is shown in Figure 7.

The impact of brake force regulator (ASR) malfunction on a vehicle towed by train will be shown through the engineering research done. In this research, different conditions of the brake lever regulator lever are simulated on the LRC device of a tow vehicle. In this research, different conditions of the brake lever regulator lever are simulated on the ASR device of a tow vehicle.

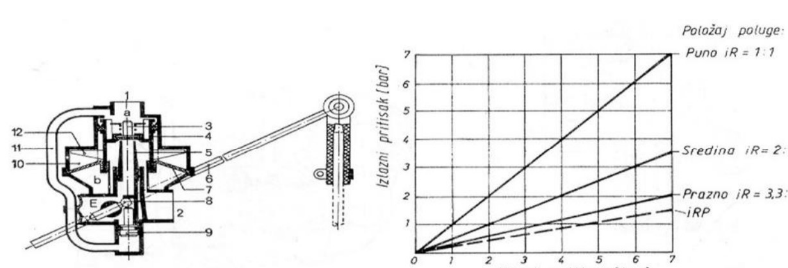

Figure 7. The appearance of ASR device for regulation of brake forces towards the rear axle at a towing vehicle

II.5. Engineering research on a braking regulator in a tow vehicle

During the research, three positions were simulated in the ASR device by the vehicle braking system (Figure 8): neutral - existing position (Figure 9), bottom position (minimum brake pressure on rear wheel brakes) and end position (top) (Figure 10), where the maximum pressure flow to the rear brakes is generated.

Especially unfavorable results were obtained in the third case when in the conditions of a simulated vehicle, maximum braking forces are generated in the rear axle brakes. As a result, when braking the vehicle (whether the straight or curved movement of the vehicle), the wheels are momentarily blocked with all the side effects resulting from this condition. The brake tracks, in this case are shown in Figure 12.

In this state of braking when moving along a curve, under a condition of locked rear wheels, when there are no adverse reactions to balance the external disturbing forces (centrifugal force, lateral wind force, etc.), stability, as well as manageability. This is especially the case if the weight of the empty semi-trailer hits the towing vehicle, which causes the towing train to disengage in the joint (saddle) and irreversibly lose control of the vehicle, i.e. the towing train as a whole (in accordance with the drawing in Figure 13).

Figure 8. The towing vehicle that was the subject of our examination

Figure 9. ASR device mounted in the towing

Figure 10. ASR device blocked in upper position under maximum brake pressure

Figure 11 and 12. Traces of braking of the rear wheels of the towing vehicle under conditions of a blocked regulator of maximum brake force

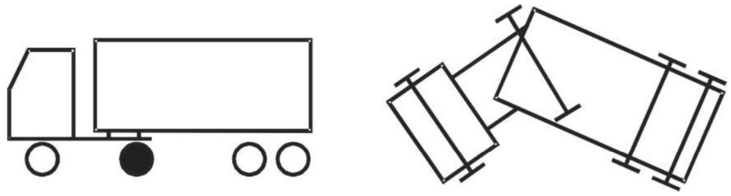

Figure 13. Disengaging of a semi-trailer towing train under the condition of locked rear wheels of the towing train

The characteristic traces obtained in this research, presented above, indicate the probable cause of a real-life traffic accident in the vicinity of Tetovo in which participants were towed by a train (a combination of towing semi-trailer vehicles) and a passenger motor vehicle.

The accident site traces (Figure 14) correspond fully to the traces shown above, indicating a defective brake force regulator of the towing vehicle, which was blocked by the maximum brake pressure flow to the rear wheel brakes, at low rear load conditions by the axel due to the empty semi-trailer.

Figure 14. Traces of braking of the rear wheels of the towing vehicle while moving the towing train in a bend

Figure 15. Disengaging of the towing train in the articular connection

This is the most disadvantageous case of vehicle wheel lock - rear axle lock. While in the case of two-axle front-wheel-drive blockage, the driver, who can sense the blockage, can regain steering by overtaking the vehicle, with the rear-axle wheel locking, this option is reduced by several times. This is especially the case when a combination of vehicles is a towing train (in this case a semi-trailer), where from the moment the semi-trailer hits its trailer mass through the coupling device and the start of the towing train break in this articular connection, there is no possibility for the driver, by any action, to regain control of the vehicle and the towing train as a whole.

III. Conclusion

In conditions of low speeds, constant adhesion conditions, low center of gravity and not very large load changes, for certain types of road motor vehicles (passenger motor vehicles, city buses, special purpose vehicles, etc.), the lack or malfunction of the braking force control device (ASR device or any other device) might not necessarily lead to dangerous traffic situations. In these vehicles, which are exploited in average traffic conditions and average adhesion conditions, with a carefully and precisely selected constant distribution of axial braking forces, it can often be ensured that no premature (initial) front-wheel locking occurs at the front axle, which is a basic requirement for braking systems in terms of brake force distribution.

For long-haul buses traveling at higher speeds, although there are no major changes in load, the performance of the braking systems is driven by the fact that they must be as safe as possible, primarily because of their function (transport of passengers).

Commercial vehicles, heavy truck vehicles, as well as vehicles for the transport of dangerous goods are the most characteristic in terms of brake system performance and regulation. These vehicles are used for long distances, with numerous frequent and large possibilities for changing adhesion conditions, large masses of the vehicles themselves and large load changes are factors that require efficient and precise regulation of braking forces along with the axles of the vehicles. On top of that, it is often the case for different vehicle configurations (towing trains) that each part of the traction system has a separate braking system and thus separate control devices. Because of all this, the malfunction of the brake force regulating devices would be dramatically manifested, which is an example in this paper.

Therefore, no matter what braking force control systems they are in question, they must be kept in perfect working order. Modern vehicles have modern electronic systems for precise control of the braking forces on the axles or all wheels of the vehicle (including integrated electronic systems including ABS, ESP, ASR, etc.), but of course they must be provided for in the case of failure, i.e. malfunction of the electronic system, basic braking force regulation on the axles of the vehicle to provide stability and driveability of the vehicle during braking, that is, braking characteristics as if it were a vehicle without an electronic control system.

The authors hope that this paper may provide an impetus to improve the technical and specialist reviews of the braking systems and, within that framework, the braking force control systems, to improve traffic safety.

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