DETERMINATION OF THE FRICTION COEFFICIENT OF THE HEAVY-DUTY DISC BRAKES OF AGRICULTURAL VEHICLES

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Abstract:
This article discusses the braking system of a heavy-duty engine for the determination of the friction coefficient. The agricultural vehicle progresses at 40 km / h speed; its weight is 30,000 kg. While braking such a heavy vehicle, a significant amount of heat is released as a result of the disc brake's friction. A significant part of the resulting heat is removed from the system using oil cooling. The cooling oil lubricates the various components and affects the frictional conditions significantly. This article describes the construction of the braking system. It contains a description of the measurements on the test bench and the evaluation of the results. This study determines the frictional performance and describes the method for determining the friction coefficient of a given construction. The author shows the changes in the friction coefficient depending on the pressure and the temperature, and draws conclusions from the results.

Keywords: AGRICULTURAL VEHICLE, DISC BRAKE, BRAKE FLUID, BRAKING, FRICTION, STRIBECK CURVE

1. *Presentation of the braking system*

The brake-system with disc forming the subject of the study can be found in the hub. During the operation of the vehicle the brake system can have two statuses. When there is no braking, the brake-discs are in open position and they are rotating. The brake-house is filled up with fluid up to 19 mm above the mid-axis. The cooling oil is flowing freely between the discs and withdraws heat from the system through the heat-exchanging processes. During the experiment the braking took place in 2 seconds During the braking the hydraulic system is compressing the rotating brake-discs, they are closing, and there is significant friction between the discs. The cooling oil participating in the heat-withdrawal is leaving from between the discs. When the vehicle is stopped through emergency braking there is a temperature of 298 C° between the discs due to the friction. Due to the friction the friction work is transforming almost in full into heat. The friction work always appears as loss in the energy balance. The brake-fluid flowing in between the brake discs (reopening after the braking) is removing the friction heat from the system. If there is no heat withdrawal then it would lead to the fast fatigue of the equipment since due to the big heat burden the surface level of the discs would dilate to a great extent and contract compared to the layers under the surface. The process would lead to the breaking of the surface layers of the parts.

Besides removing the heat the brake fluid flowing in between the brake discs has also the role of lubricating the machine elements participating in the friction. In this way the surface deterioration occurring due to the friction force can be prevented.

When the breaking is over, the break-discs are opening again, brake-oil (fluid) is flowing between them. The brake-oil is taking over a significant part of the occurred heat from the equipment, then due to the centrifugal force it hits the wall of the brake-house. In this way a portion of the received heat is given away to the environment. The heat that remains in the system is being lead away from the system by a water-cooling oil-cooler.

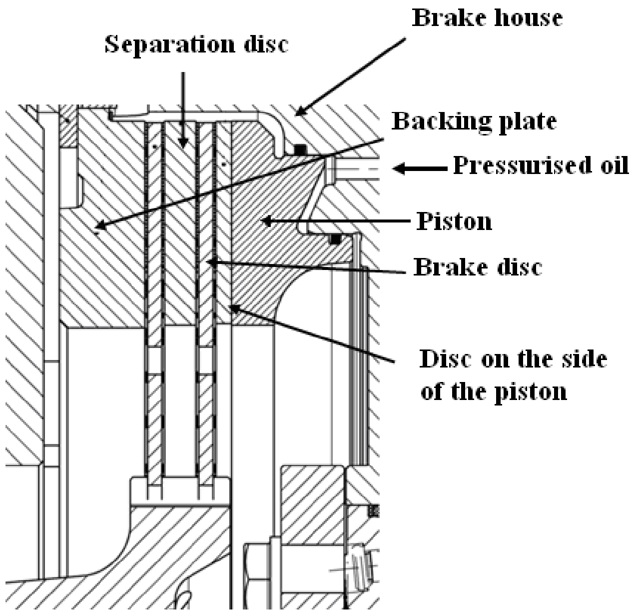

Figure 1 *– Main elements of the braking system found in the hub.*

The two brake-discs are made of steel, the supporting disc, the separating disc and the disc on the piston-side is made of grey cast.

The brake discs were supplied on both sides with a special 1-mm thick paper. The paper layer is made of fibrous sheets which are soaked with resin and there is friction-modifying additives being added. The main task of the fractioning layer consists of assuring the big friction factor.[8]

The fractioning substances are paired with cast iron, steel, aluminium counter-surface. The heat-resistance and wear-resistance are highly required. The fractioning substances shall be of high solidity. The friction factor and the size of the fractioning lining may vary at the smallest possible extent in function of the temperature. [2] The wearing of the brake-lining are influenced by the same parameters like the friction (burden, speed, temperature) [6]

2. Measuring at the trial bench, measurement results

The measuring took place on a Greening bench that examines the fly-mass wheel-brake structure and braking effect. The equipment can be used to examine the braking effect of the undercarriages with an axis burden of 2-13 tonne occurring within the realistic operational circumstances, simultaneously with the comparing wear measuring. The data recording took place with 16-channel data-recording equipment of type Hottinger Spider Mobil.
As a study unit there is the half of a bridge-house closed with a holding disc, and the bearing-hub structure is fitted onto the equipment. The bridge-house half is situated in the stator of the equipment.
The external cooling with air, the „counter-wind" cooling effect is assured by the air that is flown by a ventilator through the piping system with a cross section of 0.4 x 0.6 meter.

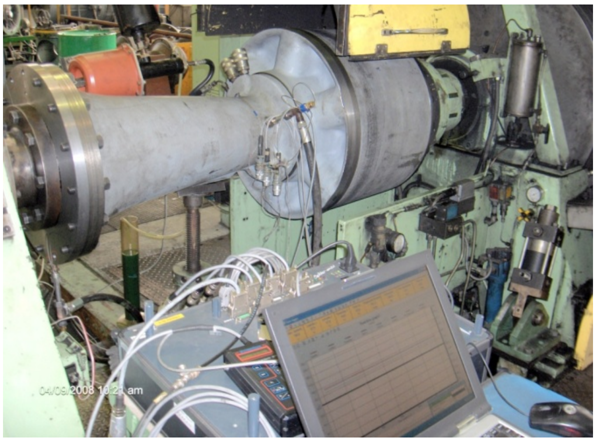

***Figure 2** – Bridge house prepared for measuring*

During the examination the temperature was measured on the separating disc. The separating disc is 12 mm thick. It contains two heat sensors in a 50-mm deep bore with a 3-mm diameter.
The first heat sensor was built into the middle of the separating disc, meaning at 6 mm from the edge, the other heat sensor is 3 mm from the disc-edge.

3. Determining the friction factor occurring between the blades of the brake system

3.1. Problems of determining the friction factor

The friction factor can be determined by using measurement data. Practically it is impossible to calculate, at least in the case of such a complicated structure.

The brakes can be categorised in the group of structure that are sometimes slipping and are sometimes steady. [4] The value of the friction factor is varying during the braking.

The value of the friction factor is determined by the following main factors – without trying to list all of them:
- structure of the fractioning equipment
- heat-condition of the equipment
- data of the vehicle's moving (speed, deceleration)
- substance of braking discs, surface characteristics, machining, etc.
- oil features
- braking frequency
- speed of surfaces slipping on each other
- the thickness of the oil-membrane between the surfaces, its temperature, carrying capacity, quality of the friction process (dry, semi-dry, clean (full) fluid-friction)

It can be proved that the temperature of the cooling oil that is touching directly the surface of the brake disc is identical in the border layer with the temperature that occurs due to the friction of the brake disc.
The author made some experiments to determine the temperature where the cooling oil is getting damaged or getting decomposed due to burden at a certain temperature. [3]

3.2 Specifying the friction mode

In our satiation it is not possible to determine the friction mode in full according to the greasing status. When considering the current structure it is most probable that we are talking about a mixed friction.
Due to the vehicle's travelling and the rotary motion of the discs there is always cooling oil flowing in between the brake discs, but it is rather likely that it can't cover uniformly the entire surface of the brake discs. During the braking when the discs are closing, a significant part of the brake-fluid is leaving through the oil canals established on the brake-discs, but because of the very short braking time not the entire oil quantity can leave from between the discs.
That is why the brake-disc has a part where there is border-friction.

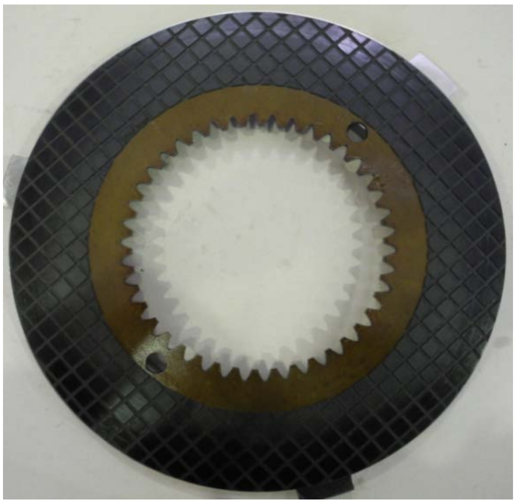

***Figure 3** – Outer side of the brake-disc supplied with a fractioning layer*

In the case of **border friction** the surfaces are separated by a thin absorbed lubrication layer of the magnitude of 0.01μm. [1]

The lubrication substance with a thickness of a few molecule layers prevents the metallic contact. It has a high pressure resistance and similarly to the crystalline substances it is capable to vary its shape. It has a wedging capacity [6]

At the part of the brake-disc where the cooling oil has left in full, there is dry friction between the brake discs.

In the case of the **dry friction** there is no lubrication between the surfaces that participate in the friction. This is when the biggest wearing appears. In such situation the rutting is rather frequent.

At the end of the 17th century Amonton described the classical friction law for the dry friction, that is the Coulomb law:

$$F = \mu \cdot N$$

where μ – friction factor

F- friction force

N- force that is perpendicular on the surface

Due to the grooved structure of the brake disc it is rather possible that the occurrence of fluid friction is very rare. Its presence is rather disadvantageous for us. Even the grooved version was introduced for avoiding this.

In the case of **fluid friction** there is fluid or a gas layer between the surfaces. The fluid respectively gas layer between the two machine elements can move freely but the friction provided by them is possible only in the case of certain conditions. (e.g. at certain pressure level)

In the case o clean fluid friction the thickness of the lubricant is bigger than the unevenness of the fractioning surfaces. There is no wearing in the case of the fluid friction except when there are abrasive substances between the fractioning surfaces or if the hydro-dynamic tensions, pressures occurring in the lubrication substance are so high that the material of the fractioning elements can't bear for long. [6]

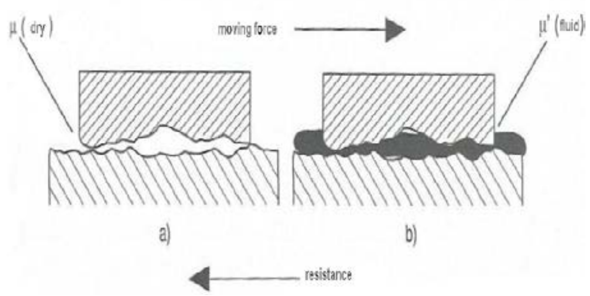

***Figure 4** - dry, rough friction (a), fluid friction (b) [5]*

In the case of the disc-based brake system it is rather likely that a combination of the above-mentioned friction modes is occurring.

There is **mixed friction** when the free-moving fluid is present at certain parts of the touching surfaces. This may happen only when the conditions required for the realisation of the fluid or gas friction do not occur. [1]

This time the metallic surfaces are getting so close to each other that they can touch metallically at certain protruding points. This friction mode has three versions:

1. Light, partial fluid-friction when the effect of the fluid friction is not significant yet. The metallic touch of the protruding points is momentary. The speed of dislocation, the specific pressure is low.
2. High-heat partial fluid friction: due to the high friction heat. The temperature of the instantaneous contact can be rather high due to the moderate cooling effect, it may cause a minimal local melting. It is likely that this case occurs in the examined brake system.
3. High-pressure partial fluid friction: occurs in the case of the high specific pressure, small dislocation speed. [6]

The list shows how the occurring circumstances influence the occurrence of the friction. It is almost impossible to take these into consideration through calculation. It is made complicated because here there are slipping and parallel surfaces, thus the classical carrying oil-membrane (such as in the case of the classical slipping bearings) may not get formed. In certain, simple situations by complying with the simplifying conditions the friction factor can be calculated, but it is always safer to determine it through measuring.

4. Determining the value of the friction factor

Szántó [6] is defining the rotary friction (which is actually a special version of thee slipping friction) as follows:

We are talking about rotary friction when all the touching or relatively touching points of two bodies are describing concentric trajectories around a rotary axis.

Per Szántó in this case the friction factor can be specified as follows:

$M_s = F_N r \mu$

Where:

M_s- friction momentum

r- radius of the rotary body

μ- friction factor depending on the operational conditions, between 0.005-0.14.

FN-compressing force

The creation of the friction is a dynamic process, changing in time, e.g. the oil can be squeezed out from the surfaces which is varying in time and we consider it static when taking into account the capacity of our measurement devices, naturally within one dimension.

We are writing the friction output for actually determining the friction factor

P is the pressure exerting onto the brake-disc element which is considered constant in function of the radius. Supposing the completely parallel surfaces and the even position.

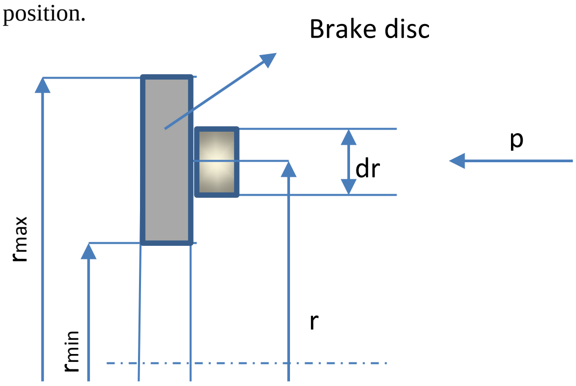

***Figure 5** – Figure helping to determine the friction factor*

The elementary friction momentum

$$dM_f = 2 \cdot \pi \cdot rdr \cdot p \cdot \mu \cdot r$$

where r is the arm of the momentum

$$dF = 2 \cdot \pi \cdot rdr \cdot p$$

pressure force applied onto the element

$dM_f = 2 \cdot \pi \cdot p \cdot \mu \cdot r^2 dr$ Since the radius is changing, it has to be integrated

$$M_f = 2 \cdot \pi \cdot p \cdot \mu \int_{r_{\min}}^{r_{\max}} r^2 dr = 2 \cdot \pi \cdot p \cdot \mu \left[\frac{r_{\max}^3}{3} - \frac{r_{\min}^3}{3} \right]$$

The friction momentum is known from measurements, the pressure exerting onto the disc is known, the geometrical dimensions rmax and rmin that is the biggest and smallest radius of the disc are also known, thus the µ friction factor can be determined, with the following specification:

Regarding the friction momentum known from the measuring the brake system has two discs, a brake disc has 2 friction surfaces, thus altogether 4 friction surfaces are creating the momentum value defined through measuring.

According to the above-mentioned since the value of the measured Mf friction momentum derives from the 4 friction surfaces, the value of Mf needs to be divided by 4. Thus:

$$\mu = \frac{M_f}{4 \cdot 2 \cdot \pi \cdot p \cdot \left[\frac{r_{\max}^3 - r_{\min}^3}{3} \right]}$$

The surfaces of the hydraulic piston (onto which the pd pressure is being applied) and the discs are different, the surface of the discs is bigger, thus the pressure exerted on them is decreasing thus the pressure applied on p is as follows:

$$p = p_d \cdot \frac{A_d}{A_t}$$

where:

Ad – surface of the piston

At – surface of the disc

The final relation:

$$\mu = \frac{3 \cdot M_f}{8 \cdot \pi \cdot p_d \cdot \frac{A_d}{A_t} \cdot \left(r_{\max}^3 - r_{\min}^3 \right)}$$

Geometrical data:

Piston diameters:	Disc diameters:
Ddmax=0,4241 m	Dtmax=0,44882 m
Ddmin=0,365 m	Dtmin=0,3 m
Ad=0,0367 m^2	At=0,0875 m^2
Ad/At =0,41943	

Summoning the constant values:

$$\mu = 35{,}93 \frac{M_f}{p_d}$$

This final relation is valid for the given brake equipment only.

(the p pressure shall be specified in Pa, that is N/m^2)

Before beginning the presentation and analysis of the measurement results let's have a look at the so-called Stribeck curve (figure 6) with which the measured results can be understood better.

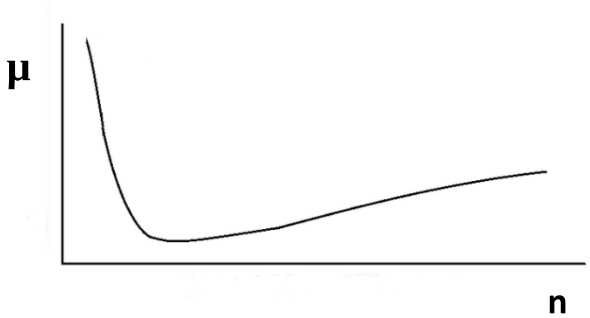

Figure 6 *- Stribeck curve*

The Stribeck curves [7] are measurement results based on experiments where the bearing's μ friction factor can be seen in function of the slipping speed of the bearing (rotation number). The friction factor achieves minimal value in function of the bearing's rotation then the friction factor is increasing again if the rotation is increasing or decreasing

There is mixed friction in the field left from the minimum point of the friction factor (that is why the μ is increasing), respectively there is border friction, and there is fluid friction in the field in the right. [9] In the field on the right side the friction factor is increasing despite the fluid friction since the speed gradient is increasing when the circumferential speed is increasing which is causing the increase of the slipping tension (σ) occurring on the oil-membrane and the increase of the μ friction factor.

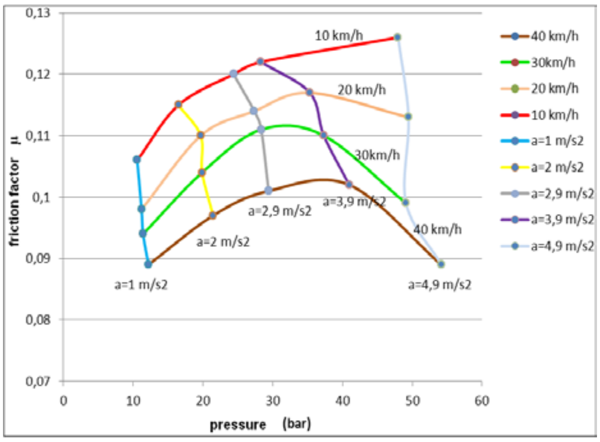

Figure 7 *– friction factor - pressure diagram*

According to my measurements the figure 7 shows the μ friction factor in function of the brake pressure, the parameter is the travelling speed 8km/h) and deceleration of the vehicle. When the travelling speed I decreasing, the friction factor is increasing, since due to the low travelling speed of the vehicle respectively due to the low rotation of the brake system and the small diameter of the brake disc the operational point is left from the μ minimal value on the Stribeck curve, and this is causing the increase of the μ. The increase of the friction factor is between 0.17 – 0.35 when the travelling speed is decreasing.

At the first approach the friction factor is constant, the change in function of the brake pressure 8the force that is compressing the brake discs) is around 10-20%, it is less than during the variation of the travelling speed. This can be justified by the fact that the friction factor is primarily a substance factor. (frictioning pair of substances, surface quality, machining, etc) and secondarily it is a flowing phenomenon, naturally the latter one can be neglected. When the travelling speed is increasing the friction factor is decreasing when the deceleration is constant. The decrease of the friction factor (with a constant deceleration) can occur only if the force that is compressing the brake discs (that is the brake pressure) is increasing. In my measuring sessions this does take place, the brake pressure is incr4easing by 10-35% when the travelling speed is increasing. With a constant deceleration the decrease of the friction when the travelling speed is increasing can take place only if the operational point of the braking is left from the minimal point of the Stribeck curve, as we have already proved earlier. It is clear that basic conclusions can be drawn from the Stribeck curve. That is why it was reasonable to present the Stribeck curve before the analysis if the measurement results.

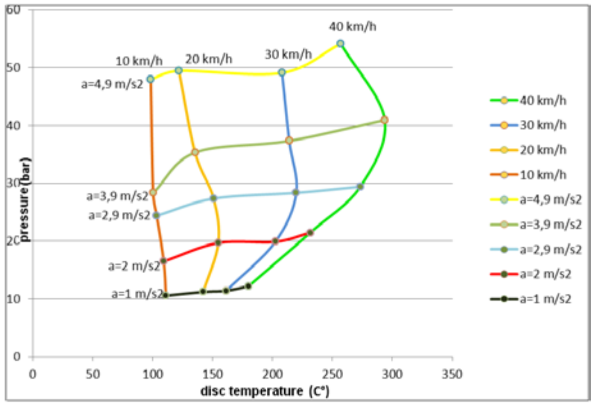

Figure 8 *– Pressure temperature diagram*

Figure 8 shows the thermal results of the braking process where the brake-pressure can be seen in function of the disc's temperature (actually the temperature of the border layer of the lubricant oil between the discs). Deceleration and the vehicle speed are the parameters. The results are clear. The higher the travelling speed and the bigger the deceleration is during the braking, the higher the extent at which the temperature of the brake-discs is increasing. The viscosity and simultaneously the friction factor are decreasing due to the increase of the temperature of the oil-border-layer. This can be compensated with the increase of the brake-pressure only which takes place definitely. Similarly when the deceleration is increasing then the heat relieved in the unit of time is increasing, the temperature of the disc during the braking is increasing, the viscosity and the friction factor are decreasing. Naturally these thermal processes are also influenced by the fact that in order to have a bigger deceleration there is need for bigger brake-friction momentum meaning the bigger brake-pressure.

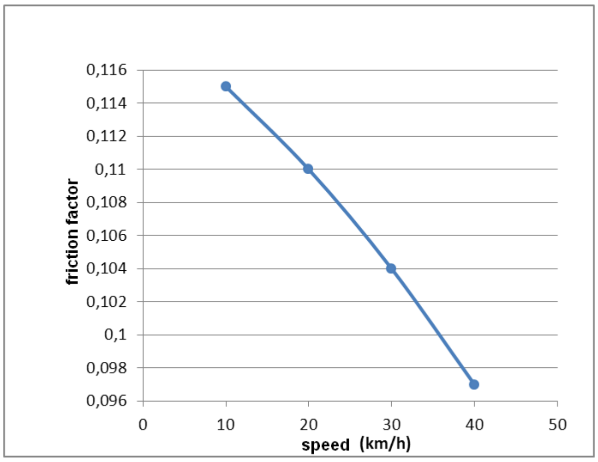

Figure 9 *– variation of the average friction factor in function of the travelling speed*

According to figure 9 the average friction factor is evidently decreasing when the vehicle1s speed is increasing. This figure was prepared with the measurement results of figure 7. This also proves that the operational point of the braking is situated left from the minimum point of the Stribeck curve.

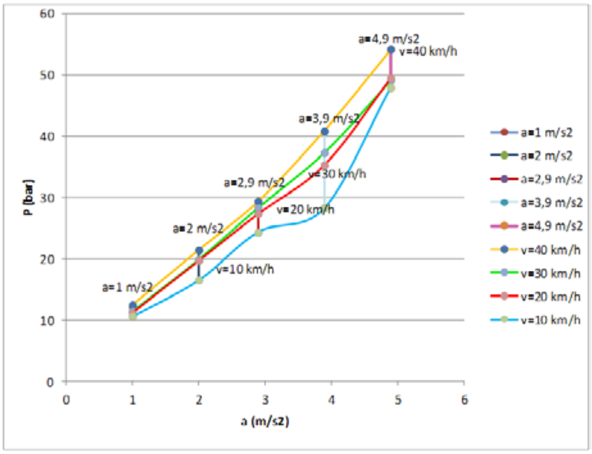

Figure 10 *– Presenting the travelling speed of the vehicle in function of the deceleration and pressure*

Figure 10 shows the various operational features of the braking. It is conspicuous that the higher the speed of the vehicle, the bigger brake pressure is needed for establishing the given deceleration. Due to the increase of the vehicle's speed the temperature of the oil-border layer stuck to the brake-discs is increasing, the viscosity is decreasing, the lubrication capacity is decreasing, the friction factor is increasing that can be compensated only with the increase of the brake-fluid's pressure.

A similar thermal braking phenomenon can be observed along a steady travelling speed when the deceleration is increasing. In this case the heat quantity relieved in unit of time is increasing, the temperature of the oil-border layer is increasing, the lubrication conditions are worsening, the friction factor is increasing, which can be compensated by increasing the brake-pressure.

5. Summary:

The study is examining the friction-thermal-energetic phenomena that occur during the braking of heavy-weight and slow vehicles. Considering the vehicle's big-diameter rubber-balloons and the slow travelling speed. The rotation of the wheel is rather moderate thus in order to achieve the required brake momentum they use several braking discs. Due to the above the operational point of the braking is left from the minimum point of the Stribeck curve, in the range of the low rotations respectively slipping speeds.

The objective of the study consists of determining the µ friction factor occurring during braking, since with such complicated friction circumstances the theoretical definition of the friction factor is practically impossible.

The introductory part of the study first defines the relation with which the µ friction factor can be calculated from the braking results (friction momentum, brake momentum, temperature). The variation of the measurement results and the friction factor that can be calculated from them is rather identical with the conclusions drawn from the Stribeck curve.

The value of the friction factor is between 0.09-0.125 in function of the operation state of the braking. When the travelling speed is decreasing and the brake pressure is constant its value is increasing by 15-25% while when the brake pressure is increasing it is increasing when the travelling speed is low, while in the case of higher speeds it is constant at the first approach when the change is parabolic.

The average friction factor is decreasing when the travelling speed is increasing (slipping speed of the brake-disc)

During the braking from a higher travelling speed and when the deceleration is increasing the temperature condition of the brake system, primarily the temperature of the oil-border layer is definitely increasing. Its influence can't be neglected in connection with the variation of the friction factor.

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