DESIGN OF VEHICLE ROAD TESTING METHOD FOR DETERMINATION OF BRAKE PAD FRICTION CHARACTERISTICS

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ABSTRACT

Friction material of brake pads is one of the most important elements of the brake because it has great influence on performance of basic tasks of braking. The following friction material properties are generally desirable: high, stable and predictable static and dynamic coefficient of friction, minimum wear characteristics combined with frictional properties that inhibit counter surface wear, adequate corrosion resistance, absence of vibration and squeal noise, acceptable costs of raw materials, processing and manufacturing technologies. Testing of material friction characteristics demands delicate procedure, because their features can not be estimated based on their chemical structure, configuration but exclusively based on experimental methods. There are two basic ways for testing of friction properties: within the brake itself or on samples, i.e. friction materials test tubes. Frequently, laboratory tests of friction characteristics are not enough, but it is necessary to subject friction materials to a series of vehicle tests on a test track or on the road before they are released as commercial products. Analysis of brake pad friction characteristic obtained by the road testing of vehicle is presented in this paper. The influence of variations of pressure in brake cylinder and vehicle speed on friction coefficient during tests is analyzed. Also, variation of friction coefficient during braking is monitored, starting with the assumption of cosine distribution of surface pressure along the brake pad.

Keywords: friction material, brake pad, friction characteristics, vehicle road test.

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Vehicle brakes are just one of the solutions which contact elements slide one over another with high slide speeds and high friction coefficients. This sets extreme demands before friction materials. They must operate at a moderately high and uniform coefficient of friction throughout the period of braking, frictional interactions must be such that friction-induced oscillations that produce squeal or chatter are minimised, materials must be resistant to wear to ensure long life, materials must possess sufficient thermal diffusivity to prevent the interface from reaching a critical temperature for loss of performance, materials must be able to withstand the thermal and mechanical loads imposed during braking operations.

Similar to other applications, the challenge for friction testing of brake materials is to replicate conditions that are representative of their full spectrum of use. Brakes operate in hot and cold environments, both wet and dry, on steep grades, on and off paved roads, with frequent stops, with all kinds of driver behaviour, and with different kinds of control systems. A brake material may perform well under one set of conditions but poorly under another; therefore, the development of acceptable performance criteria for brake materials is challenging, and most commercial brake lining tests comprise a sequence of stages to simulate a range of operating conditions[1].

Tests of brake lining materials are often conducted on the so-called 'dynamometers'. The kinetic energy needed to simulate the vehicle forces on the brakes can be provided by a series of spinning weights (inertia dynamometers) or by a motor whose power output is controlled to simulate different kinds of braking conditions that are experienced by a selected type of vehicle. Hundreds of computer-controlled, instrumented dynamometers with forced-air cooling systems are in use throughout the world. In just one dynamometer test a great deal of data are generated and the challenge becomes one of interpreting its meaning. The notion that a single value of the kinetic friction coefficient can characterise the braking performance of a given friction material is naive because the same series of brake linings can rank in different orders of merit depending on which frictional characteristics are compared.

Some investigators[2–4] have modified pin-on-disk testers to conduct brake lining studies, but those tribometers involve small contact areas and usually do not simulate full-sized brake heat dissipation, sliding speeds, or system stiffness. Relative comparisons within the same study may be useful but may not be extrapolated to full-sized brakes.

In real friction pairs, many other factors have an effect on the amount of friction. In this respect, the shape and size of the friction surface, the quality of surface treatment of the friction pairs elements and their physical characteristics, sliding speed at a friction surface, temperature of friction surface, surface pressure and its distribution on the friction surface should be mentioned, as well as some others. These curves are very specific and closely related to certain types of materials, construction and other restrictions[5,6].

This problem is especially complicated in brake friction pairs, where one of the coupled elements is made of the so-called friction material. These materials have very specific properties, but in fact are a mixture of different materials. An influence of characteristics of the friction pair on the efficiency of the braking process can be observed by analysing the expression for braking torque of braking mechanism that is given in the following form:

$$M_{\mathrm{k}} = M_{\mathrm{k}0} M_{\mu} \tag{1}$$

$$M_{\mu} = M_{\mu 0} M_{\mu i} \tag{2}$$

where M_{k} is braking torque, which is realised by braking mechanism – the drum or the disk brake; $M_{\mathrm{k}0}$ – part of the braking torque which does not depend on the coefficient of friction; M_{μ} – part of the braking torque which is a function of friction coefficient, which is further broken down into components $M_{\mu 0}$, $M_{\mu i}$ that are the result of constant value of friction coefficient μ_0, and variable value of friction coefficient μ_i, respectively.

A number of factors are influencing the value of μ_0 and nature of the change of μ_i, as noted above. These factors can be grouped, studied and evaluated according to types of loads, working modes, external conditions, physical and chemical properties of friction pair materials. In this sense, the general friction model of the friction pair, which includes characteristic physical values, relevant for thermal and mechanical loads, is shown in the implicit form, as follows:

$$\mu = f_g(\mathrm{WF}, \mathrm{PF}, \theta, p_{\mathrm{s}}, \ldots, \mathrm{DP}, \mathrm{MP}, \mathrm{EC}, \ldots) \tag{3}$$

where WF is work of friction, PF – power of friction, θ, p_{s} –temperature and normal pressure on contact surfaces, respectively, DP – shape, size and condition of contact surfaces, MP-material properties, EC – environmental conditions. The factors WF, PF, ..., DP, MP, EC, ... in expression (3) should be considered in the complex form due to the actions and interactions of multiple individual influencing factors. In the case of complex factors, WF – work and PF – power of friction, it emphasizes the interplay among the individual parameters θ, p_{s}, v_{k} – temperature, surface pressure, sliding velocity of the friction pair, respectively. In this sense, an expression (3) for the model of friction can be further developed and more concreted:

$$\mu = f_{\mathrm{c}}(\theta, p_{\mathrm{s}}, v_{\mathrm{k}}, \ldots, \mathrm{DP}, \mathrm{MP}, \mathrm{EC}, \ldots) \tag{4}$$

with special emphasis on the complex influence of sliding velocity v_{k}, the thermal and mechanical loads of friction pair – and, therefore, its properties in terms of stability characteristics – braking efficiency, lifetime, noise and vibration.

The form of expression (4) can be further identified and mathematically interpreted depending on the applied approach, a number of factors included and test conditions[5,6].

It is a bit simpler case if you examine friction for one particular brake, i.e. for the constant parameters that determine the structure and dimensions of brake (DP = const) and applied materials (MP = const, EC = const). Then the friction coefficient can be mathematically modeled to be expressed by a polynomial form:

$$\mu = k\ \theta^{\alpha} p_{s}^{\hat{a}}\ v_{k}^{\tilde{a}}, \qquad (5)$$

where k, α, β and γ are coefficients dependent on the type and dimensions of the brake and applied materials (friction material and metal). These coefficients can be determined experimentally, by conducting a series of tests according to the appropriate program (method of planning the experiment)[7–9].

EXPERIMENTAL

LABORATORY TESTING OF BRAKE PAD FRICTION CHARACTERISTICS

Testing of material friction characteristics demands delicate procedure, because their features can not be estimated based on their chemical structure, configuration or on other data used for estimation of metals and alloys, but exclusively based on experimental methods. Friction properties of brake pads depend on several parameters of operating conditions, first of all on temperature, surface pressure and sliding speed at friction surfaces.

Data required for the accurate characterisation of friction materials is acquired under controlled conditions in the laboratory and on the vehicle. In order to effectively interpret the acquired data, engineers must be familiar with both the procedures and equipment utilised. Many variables, such as timing, cost, sample availability and data obtained from a particular test, are considered when selecting a testing methodology appropriate to the engineer scope of work.

To reduce preliminary material qualification costs and to facilitate research, a variety of laboratory-scale test machines has been developed. These range from massive, inertial dynamometers with electronic controls and sensors to small, rub-shoe machines that can sit on a bench-top. Some off-vehicle test systems involve instrumented skid pads onto which a fully loaded vehicle can drive and apply the brakes. Instrumented roll-on-type systems can test one set of vehicle axles at a time. The amount of data obtained from this wide range of tests varies greatly, and friction data from one type of brake test may not directly correlate with that from another type. Added to this concern is the fact that many of the larger dynamometer units are custom, one-of-a-kind units. Therefore, data for different materials are usually ranked in relative terms within the confines of the given test method, and can agree between one method and another.

The following summarises the various levels of brake material testing:

I. Vehicle road tests,

II. Vehicle skid-pad tests,

III. Vehicle drive-on dynamometers (in-ground or portable),

IV. Inertial dynamometers (full-scale hardware),

V. Inertial dynamometers (sub-scale hardware),

VI. Laboratory tribometers.

While vehicle tests are expensive, time-consuming and subject to road conditions and weather variability, brake dynamometer testing in the laboratory is faster and less costly to screen or verify friction material characteristics. The two major types of brake dynamometers are commonly used: the inertial dynamometer which evaluates a full-size brake or a brake system and simulates vehicle braking well, but is time consuming and expensive, or a smaller Chase dynamometer that features low capital expenditure and shorter test time using a small friction material sample against a large drum. The Chase dynamometer does not simulate brake conditions as well as the inertial dynamometer, and therefore is used primarily for rapid screening and/or for quality control only.

Vehicle brake simulations are conducted on an inertial dynamometer (Fig. 1). To simulate the kinetic energy of the vehicle mass moving, the dynamometer utilises mechanical mass fixed in increments to a rotating shaft. An electric motor is responsible for bringing the rotating mass up to a speed set point. Once the set point is reached, the motor releases control, and the braking system is responsible for bringing the rotating mass to a stop. The energy dissipated during braking can be equated to the energy dissipated during braking in a vehicle. To accommodate multiple vehicle platforms, dynamometers utilise a stepped shaft that accepts fixed increments of inertia. To prepare a vehicle for testing, the following equipment is required: transducers (torque, pressure, temperature, speed, acceleration,

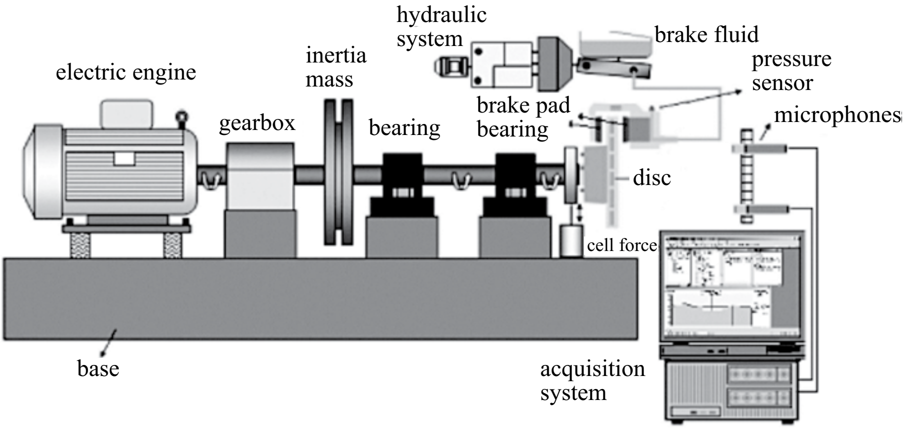
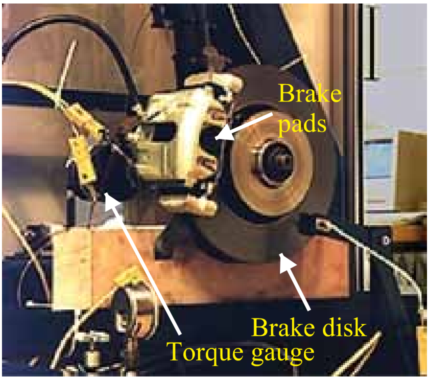


Fig. 1. Brake inertial dynamometer[10]



a

b

Fig. 2. Laboratory test stand for testing of disc brake friction characteristics

noise, etc.), signal conditioning (equipment that scales and/or linearise the output of the transducers, i.e. 0 to 50 bar is scaled to a 0 to 10 V signal for input into the data acquisition equipment), data acquisition software and hardware ('acquires' the data from the various transducers at a specified sample rate; the data acquisition software stores the data in a format that is convenient for data reduction).

Inertial dynamometers are used for testing of: friction characteristics, durability and influence of friction pads on metal element life time, dimensional stability, behaviour in conditions of extreme heat and cold and noise (including the sounds inaudible to human ear).

A slightly different laboratory test based on the use of real vehicle disc brake is presented in Fig. 2. The subassembly consisting of a disc braking system and suspension system where the propulsion, i.e. acceleration of a disc is achieved by electric engine, is presented in Fig. 2*a*. Electric engine, directly connected to the brake disc through gear box, controls deceleration independently from braking force. This technique is more convenient for noise tests (squealing), but it is limited to low speeds. Described equipment presents a compromise between the flexibility of simplified laboratory testing and relevance of the road tests. Brake installation pressure, brake torque and disc temperature are measured during tests. A transducer mounted on the drive shaft measures brake torque. The friction coefficient can be calculated if disc radius is known[11]. The disc braking system and suspension system on the vehicle where the propulsion is achieved by its own internal combustion engine is shown in Fig. 2b (Ref. 12).

VEHICLE ROAD TESTING OF BRAKE PAD FRICTION CHARACTERISTICS

Vehicle testing procedures vary as widely as dynamometer procedures. Examples of vehicle procedure test objectives include: certification testing, durability testing, and product development. Performing vehicle testing is more complicated and expensive than dynamometer testing. In order to prepare for a vehicle test, the following must be considered:

• timing – vehicle testing typically takes longer than dynamometer testing (the dynamometer can be run unattended, the vehicle can not);

• staffing – scheduling test drivers with appropriate skill levels in a manner that maximises efficiency in vehicle run-time is difficult;

• facilities – facilities for the installation of test hardware, installation of transducers, signal conditioning and data acquisition are extremely specialised and require the coordination of multiple disciplines;

• inspection – inspections typically occur at kilometer intervals and frequently must be performed outside of 'normally' scheduled shifts to maximise vehicle run-time.

A direct correlation between dynamometer and vehicle test data is not something that just 'occurs' without a considerable amount of planning. In most situations, successful vehicle testing is moved to the laboratory to decrease cost and increase testing efficiency. To develop a dynamometer procedure that correlates with acquired vehicle data, the following must be considered:

• what exactly is being correlated (wear, noise, performance);

• which brake applies or sequences from the vehicle test are candidates for inclusion in a dynamometer control program;

• what is the acceptance criteria for correlation;

• how will correlation be reported (correlation coefficient, iso-plot, etc.);

• will each test on the dynamometer be compared to a baseline set of vehicle data, or will relative comparisons be made between the dynamometer data sets.

Common properties successfully correlated between vehicle and dynamometer tests include: noise, wear, performance, judder, torque variation.

Improving correlation between vehicle testing and dynamometer testing is possible, but requires much work. Steps needed are:

• determine vehicle procedure to be correlated,

• scrutinise vehicle procedure and revise to account for 'real world' actual practices,

• place an emphasis on developing a procedure that is repeatable and reproducible

• perform study to determine correlation between vehicle tests executed using the same procedure (baseline correlation coefficient),

• determine what quantities can reasonably be correlated on the dynamometer with consideration for variables that are exclusive to vehicle or dynamometer testing,

• develop dynamometer procedure that attempts to correlate specific quantities from the vehicle test,

• conduct dynamometer testing, review data and modify control program until desirable correlation coefficient is achieved.

While it is possible to improve correlation between data obtained on a test vehicle and data obtained on a dynamometer, it is extremely unlikely that dynamometer testing, or any other modelling or simulation testing, will ever fully replace vehicle testing[11].

Cold tests of brakes are performed during road tests. Variations of characteristic values: v – speed, p_s – surface pressure and θ – temperature, during cold brake tests are shown in Fig. 3.

A part of the applied measurement system for determination of drum brake operation characteristic in road conditions shown in Fig. 4, includes: brake cylinder pressure transducer, brake torque transducer, angular velocity transducer and

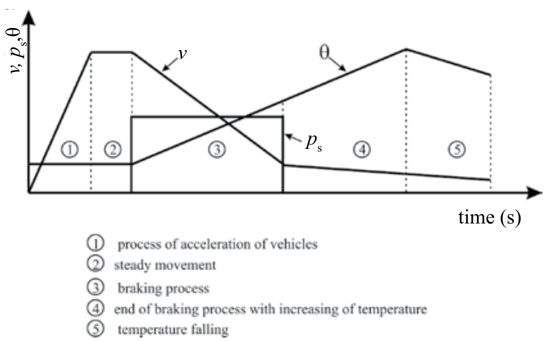


Fig. 3. Idealised schematic review of the influential factors on the coefficient of friction during cold braking test

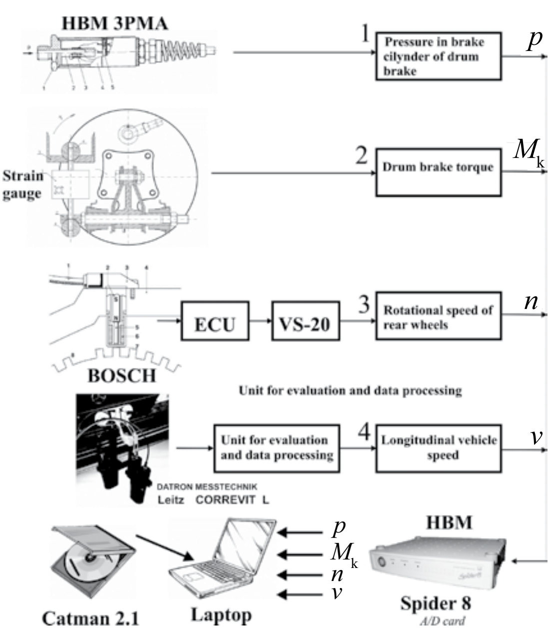
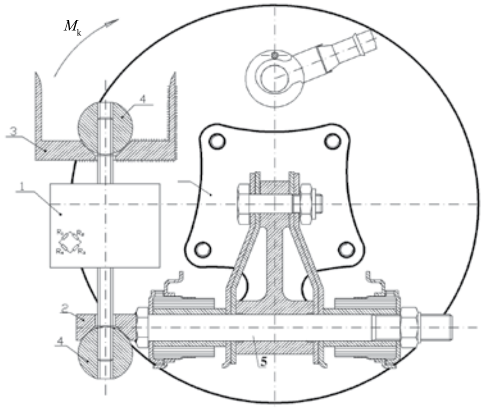


Fig. 4. Measuring chain for analysis of drum brake friction coefficients in road conditions[13]

longitudinal vehicle speed. During braking, activating forces, F_s, move apart the brake pedals, which, leaning on supports, come into a contact with the drum. At the same time, reactive brake torque acts and transmits to brake pedals trying to rotate them in the direction of rotation. Reactive torque mentioned, identical by intensity to the brake torque, is transmitted through pedal supports and brake cylinders to pedal carrier made from sheet metal.

Two design solutions of brake torque transducers specially adapted for drum brakes are shown in Fig. 5. According to the first solution (Fig. 5*a*), reactive brake torque is measured indirectly by force transducer subjected to tension during braking. Total brake torque is transferred from pedal support, through force transducer, to screwbolt that connects wheel sleeve with shock absorber and A-arm. Transducer shown in Fig. 5*b* is made in the shape of a test tube that has rectangular cross-section and on which four strain gauges are attached. Test tube ends are firmly connected to pedal support and test tube itself is connected to wheel sleeve by two screwbolts. Total reactive brake torque is transferred from brake pedal supports, through test tube, to wheel sleeve and then to elements of suspension system. Brake torque subjects the test tube to bending and that is the case of bending of console subjected to action of concentrated force at the end of console.



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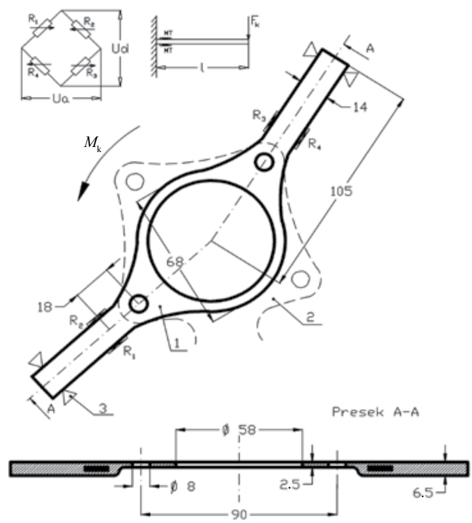
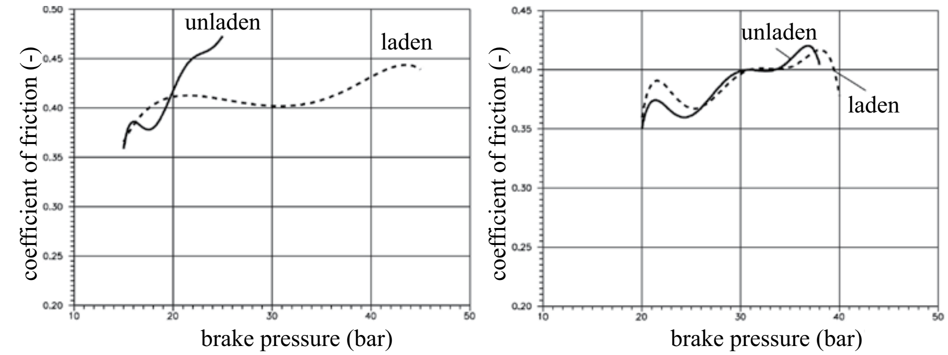


b

Fig. 5. Design solutions of brake torque transducers *a* – indirectly, through force transducer, *b* – with strain-gauges[13]

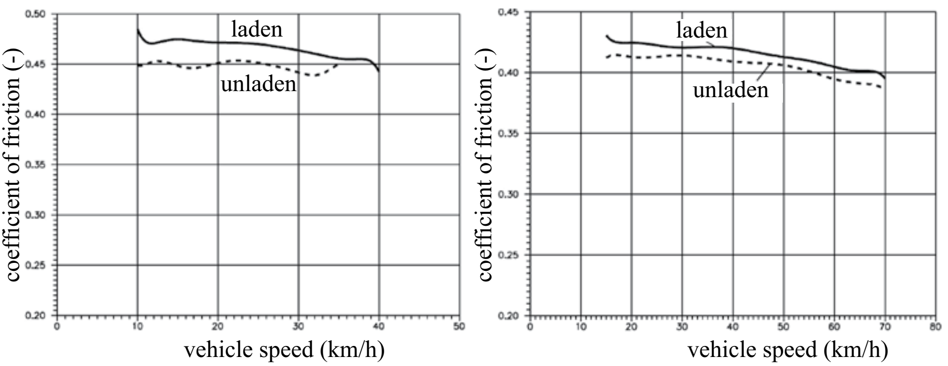
RESULTS OF ROAD TESTING

Based on acquired signals, the influence of brake cylinder pressure variation and vehicle speed on friction coefficient during tests is analysed and illustrated in



a *b*

Fig. 6. Variation of friction coefficient with the variation of pressure for unladen and fully laden vehicle at initial speed of $v_0 = 40$ km/h (*a*) and 80 km/h (*b*)

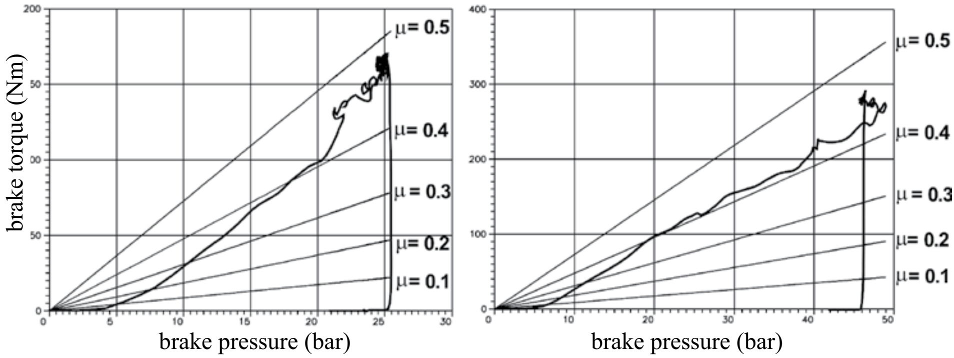


a *b*

Fig. 7. Variation of friction coefficient with variation of speed for unladen and fully laden vehicle for speeds up to $v_0 = 40$ km/h (*a*) and 80 km/h (*b*)

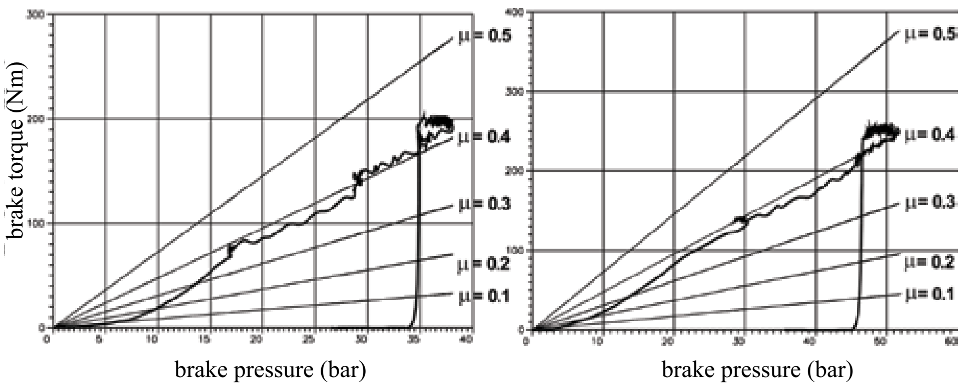
Figs 6 and 7. The increase of friction coefficient with the increase of pressure is obvious for both initial speeds of (40 and 80 km/h) while braking. The increase is more intensive for speed of $v_0 \approx 40$ km/h and for the case when vehicle was unladen. The influence of the vehicle speed is less obvious and declination trend with the increase in speed is present in all cases[13].

Figures 8 and 9 present another way of analysis of friction coefficient variation with pressure for initial speeds of $v_0 \approx 40$ and 80 km/h and for unladen and fully laden vehicle. Measured brake torque is compared to analytically determined brake torque, with the assumption of cosine distribution of pressure along brake pad, for different values of friction coefficients (from 0.1 to 0.5). It is obvious, especially for the case of fully laden vehicle, which values of friction coefficient at pressures above 20 bar are in a good agreement with analytically obtained curves.



a *b*

Fig. 8. Comparative analysis of measured and analytically determined brake torque aimed at determination of friction coefficient for unladen (*a*) and fully laden vehicle (*b*) at $v_0 \approx 40$ km/h



a *b*

Fig. 9. Comparative analysis of measured and analytically determined brake torque aimed at determination of friction coefficient for unladen (*a*) and fully laden vehicle (*b*) at $v_0 \approx 80$ km/h

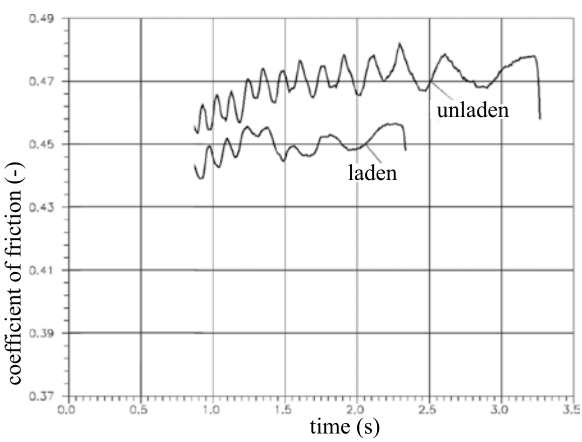


Fig. 10. Variation of friction coefficient during brake test at $v_0 \approx 40$ km/h

Variation of friction coefficient during braking may be determined based on results obtained by experimental tests and on assumption of cosine distribution of surface pressure along brake pad. As an illustration of methodology applied, variation of friction coefficient during testing time with initial speed of 40 km/h is presented in Fig. 10 (Ref. 13).

CONCLUSIONS

A number of materials tests (compression tests, hardness, thermal conductivity measurements, etc.) are employed during the development of brake materials and additives, but the final qualification test for brake materials involves extensive on-vehicle tests with full-sized components. Braking performance is influenced not only by friction materials and vehicle design, but also by a driver behaviour, vehicle condition, brake pads condition, and lastly by environment in which the vehicle drives. Possible influences of the brake system control part, engine braking and wheel space aerodynamics may be added to already listed influences. Hence, laboratory tests can not preci sely simulate the driving conditions. Friction materials functional characteristic testing includes determination of material characteristics such as friction and wear under important influence factors. This technique has the disadvantage of not being capable of separating the effects of speed, temperature and run-in, which all vary during each brake application.

All mentioned before justifies the development of road test methodologies, based on which, time variation of friction coefficient of drum brake pad friction materials is determined and the influence of load, speed and rear brake cylinder pressure is analysed. Developed measuring system also enables real time evaluation of operation characteristic deterioration with the increase in temperature (fading), an occurrence specially expressed in drum brakes. Designed testing method can be supplemented by measuring the brake noise so that it can check whether there is a relation between the change of coefficient of friction and the occurrence of noise.

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