# Application of an inertia dynamometer to check braking performance against theoretical predictions


## *Abstract*

Friction is a typical stochastic process, characterised by a number of random influences. It is almost impossible to predict performance and reliability of such mechanisms theoretically or in an analytical form. Evaluation of tribological properties of friction mechanisms is a rather complex task, and that is why experimental methods are broadly used. It particularly applies to brakes and braking systems of road vehicles. There is a general awareness that vehicle brakes have to be thoroughly tested and approved in accordance to various regulations and road safety requirements, so as to evaluate their performance confidently.

In order to provide experimental verification of theoretical predictions of performance and reliability characteristics of friction brakes and road vehicle braking systems a comprehensive testing facility is developed at the Faculty of Mechanical Engineering of the University of Belgrade. The most important part of it is the LCBT - Laboratory for Clutch and Brake Testing. This Laboratory is equipped with a new line of six inertia dynamometers, all being self-developed and locally manufactured. The patent-pending and compact designed dynamometers are fully automated, i.e. computerised and on-line data acquisition, data processing and test results presentation is provided to enable full-scale testing of all types of brakes and other friction mechanisms, including dry and oil immersed clutches and multi-plate brakes used in cars, commercial and off-road vehicles, and other earth moving equipment. The paper describes how the inertia dynamometers developed at the LCBT Laboratory are used for various tasks with respect to type approval testing, quality assurance and quality control, research and development in the field of friction mechanisms for road vehicles.


## *1. INTRODUCTION*

Tribological properties (friction and wear) of friction mechanisms used in different motor vehicles, their trailers and other earth moving machinery depend on a number of influencing factors exerted by service conditions, design of the friction mechanism, and the properties of materials used to make it. As generally recognised, brakes and clutches realise their function in a vehicle by means of frictional forces developed between elements in relative motion at different sliding speeds, with one element usually revolving while the other is often being still-standing.

Evaluation of tribological properties of friction mechanisms is a rather complex task, since friction is a typical stochastic process, characterised by a number of random influences, why it is almost impossible to predict performance and reliability of such type of mechanisms theoretically or in an analytical form [11]. Experimental methods are therefore broadly used to evaluate performance of brakes and clutches. It particularly applies to brakes and braking systems, which have to be tested and approved in accordance to various regulations and prescriptions related to road safety [9, 22].

However, experimental evaluation of tribological properties of friction mechanisms is time consuming and may become very expensive, because a variety of different test conditions and test methods may be applied. Although different methods for testing of brakes and/or braking systems may be applied under road or laboratory conditions, all of them may be classified as follows:

- I - Evaluation of chemical and physical properties of friction materials, such as chemical composition, hardness, modulus of elasticity, moisture absorption, oil absorption etc.,
- II - Small sample (or specimen) based testing of friction and wear, using different test machines, like Ranzi - Cuna, Krauss, SAE-Chase, etc., operating under constant pressure or constant speed,
- III - Full-scale test benches often called inertia dynamometers,
- IV - Rolling-road test benches, and
- V - In-vehicle testing in real service conditions or on the test tracks.

These methods are different with regard to their purpose and scope. Evaluation of friction material with respect to its chemical and/or physical characteristics in addition to the small sample friction and wear testing procedures is very convenient for conformity of production checks and very popular because of that, but that would not be enough to determine the rating performance of a given brake, for example.

Friction mechanism used in road vehicles and other moving machinery is usually a part of complex equipment, device or system like braking system, transmission gear or similar. That is why road testing is more suitable for evaluation of the overall characteristics of such an equipment, device or system and therefore this represents the most objective method. However, road testing creates a number of inconveniences, particularly with regard to repeatability, high scattering of test results, long lasting and generally high costs.

Rolling-road tests intend to gather together road and in-house or laboratory test conditions in a unique test method and such a special test equipment is often used for some conformity tests of vehicles with respect to braking, like in the case of periodical inspection of vehicles, and for the on-condition diagnostic tests used in maintenance technology. Therefore, full-scale brake laboratory test methods are more suitable for evaluation of the friction mechanism itself and its components by providing test results quicker and cheaper. Besides, the results are then more strictly tied to the mechanism under test, by means of eliminating side effects produced by adjacent elements or equipment etc. The results may sometimes become less realistic and somehow difficult to understand and explain. But if the test is performed at a full-scale dynamometer, using test program based on well designed simulation technique, the obtained results usually are satisfactory and they may be easy to understand and explain. That is why full-scale inertia dynamometer tests are widely used for research, development and quality control [10, 19, 21] and in the standardised form for type approval and certification purposes [9, 22].

In some cases there is an idea to standardise the test sample [18]. Although certain advantage related to flexibility of enabling quick testing and high repeatability of test conditions in such a way may be provided, this type of tests is more or less similar to the small sample testing, because the results of "standardised scale" tests are hard to correlate with those corresponding to the "full scale" mechanism.

## 2. LABORATORY FOR CLUTCH AND BRAKE TESTING

The LCBT - Laboratory for clutch and brake testing of the Institute for motor vehicles of the Faculty of Mechanical Engineering, University of Belgrade, is in operation since 1966. It now represents the unique testing facility of this type in Yugoslavia, and also in this part of Europe. The Laboratory is accredited by the governmental authorities as an official technical service for type approval testing of vehicles with regard to braking, according to ECE Regulations No. 13 and 78 [22], and for other friction mechanisms certification procedures according to national regulations. The accreditation process with regard to ECE Regulation No. 90 concerning replacement brake linings is in due course.

Along with the type approval and other certification activities, this Laboratory carries on various research and development projects, in collaboration with a number of local manufacturers of cars, commercial and other vehicles, brakes, clutches, friction materials and other friction mechanisms and components. Very intensive co-operation with some of the most famous foreign companies in this area like Mercedes-Benz, Rockwell, Don-Mintex, and others partners like University of Palermo has also enabled excellent research results to be obtained [8, 19, 20].

In addition to the comprehensive equipment for road testing of vehicles and in particular braking system tests according to ECE Regs. 13 and 78, this Laboratory is equipped with a full line of inertia dynamometers designed to simulate application modes and loading of brakes and clutches in different vehicles, under in-service or usage conditions. Several type ranges or families of inertia dynamometers are developed, all patent pending. Each family is composed of several units, intended to be applied for testing brakes and/or clutches of different vehicle categories. Six different stands are now in use at LCBT, and several other units were developed to meet the needs of different customers and therefore they were built and sold to a number of industrial enterprises.

The PSK line of dynamometers comprises several units. Figure 1 shows one of them, designed for testing small and medium brakes used in cars, vans, and light trucks and trailers. The other unit (Figure 2) is designed to provide testing of brakes used in heavy commercial vehicles. All units are designed so as to be tailored following the specific needs of an end user.

The dynamometers of PSS line are designed so as to enable specific conditions of testing to be duplicated following the needs to test dry clutches used in agricultural tractors (Figure 3) or road vehicles (Figure 4), but also for oil immersed clutches and brakes for off-road vehicles, caterpillar tractors and other heavy equipment.

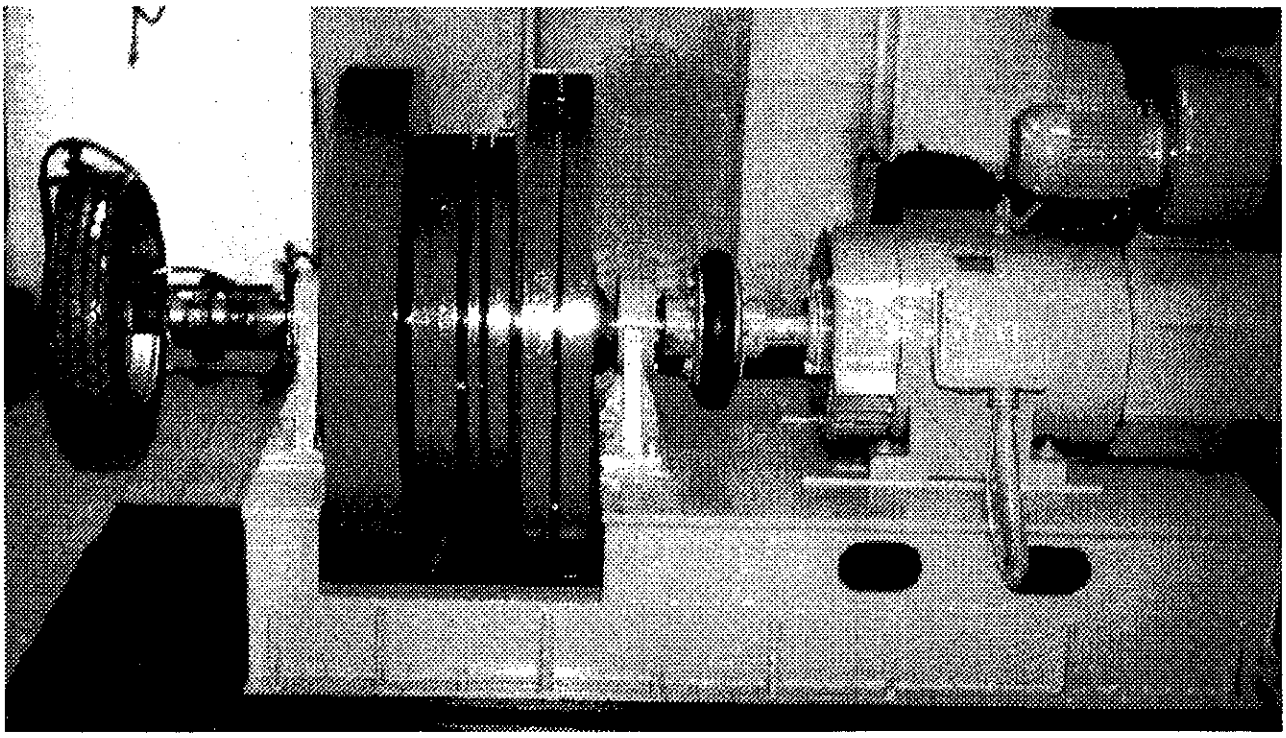


*Figure 1. Car and light commercial vehicle brake dynamometer PSK-20*

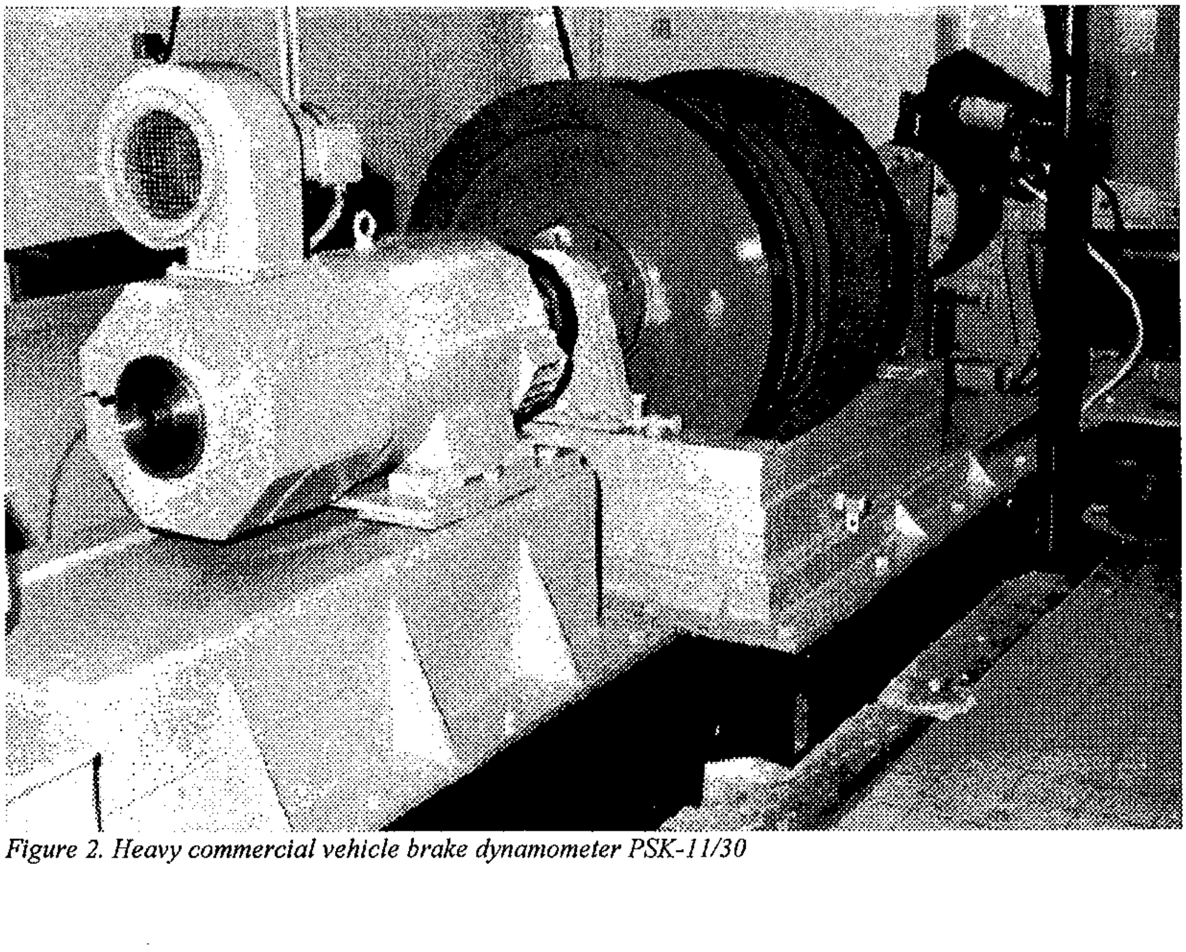


*Figure 2. Heavy commercial vehicle brake dynamometer PSK-11/30*

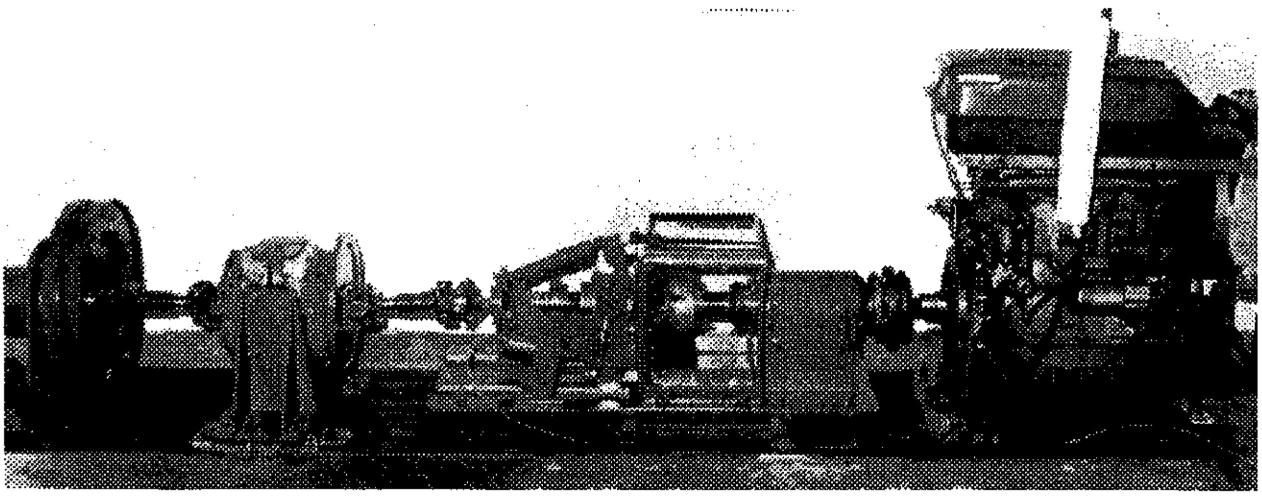


*Figure 3. Agricultural tractor clutch dynamometer PSS-10*

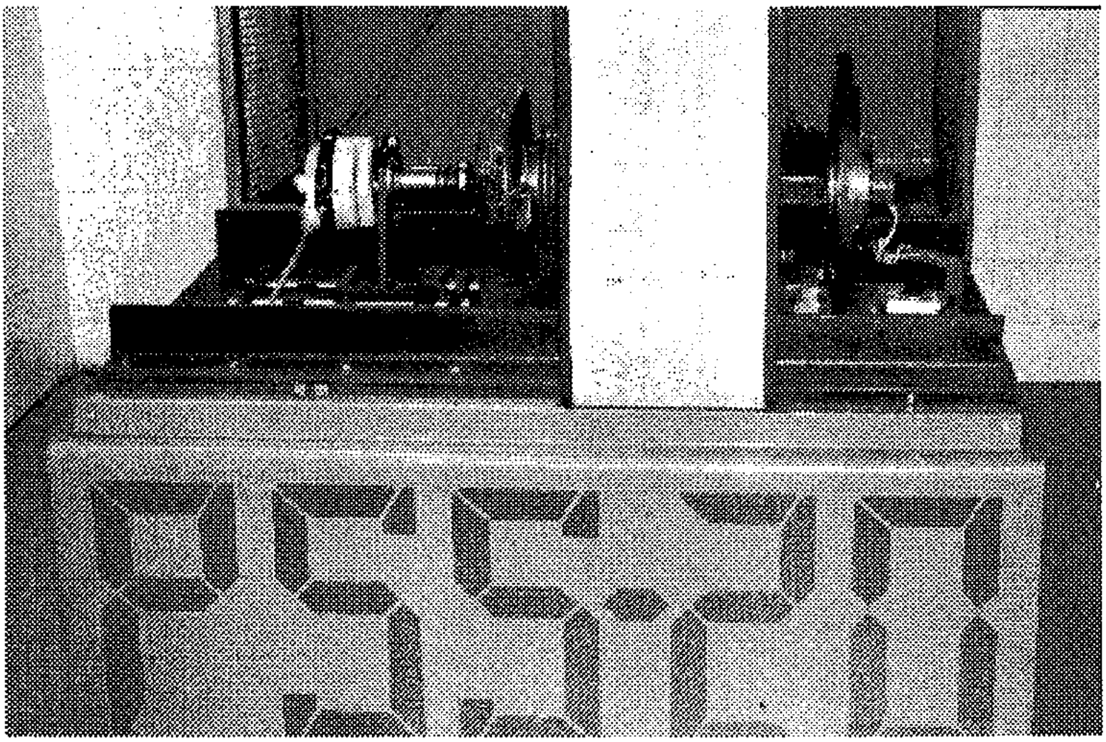


*Figure 4. Car and light commercial vehicle clutch dynamometer PSS-20*

## 3. FULL SCALE INERTIA DYNAMOMETERS

Since all friction mechanisms perform their function by converting kinetic energy into the thermal one, the task of an inertia dynamometer is to enable to a tested brake to be loaded by the appropriate portion of the vehicle's total kinetic energy. This energy is duplicated by the portion of the vehicle's total inertial mass driven at the appropriate speed, corresponding to that of the vehicle.

The aim of testing a brake by means of an inertia dynamometer is to provide possibilities for transformation of the above mentioned kinetic into thermal energy by reducing the speed of revolving masses and to dissipate it to environment. This principle is realised by means of a number of flywheels to which the rotating part of the tested brake is firmly connected. Those flywheels are accelerated by a driving motor to a designated speed, and then decelerated by the brake to a given final lower speed or to the full-stop.

The design of LCBT inertia dynamometers is explained in principle in Figures 5 and 6. The Figure 5. presents scheme of the brake rig PSK-20 used for testing the brakes of cars and light vehicles. The DC motor (1) drives, via coupling

(2), a set of six flywheels (3) independently mounted on the driving shaft (4). The flange (5), firmly jointed to the shaft (4), bears rotating part of the tested brake (drum or disc), while immobile flange (6), being firmly connected to the foundation (7), is used for mounting stationary parts of the tested brake (shoe-plate or caliper). By means of a specific device, each of flywheels can be connected to the driving shaft (4) separately or in a required combination, providing in such a way different inertia (from 10 to 200 $kgm^2$). In addition to that, in the case of test rig intended for testing commercial vehicle brakes (PSK-30) there is an auxiliary constant-ratio gear box, which provides much higher inertia (from 90 to 1800 $kgm^2$) at lower speed (maximum $50s^{-1}$), as required for testing of heavy vehicle brakes.

Since the DC motor with a tyristor controller gives a continuous speed variation, up to 150 s-1 the total kinetic energy of the dynamometer can be changed in wide limits, so as to adapt to the requirements. The testing sequence comprises various type of braking from higher to smaller speeds ("snub-braking"), or to the stop ("full-stop" braking). The stand also provides possibilities for simulating down-hill braking at constant speed and/or constant torque.

Both in the Figure 1 and in the scheme of Figure 5 an important feature of the LCBT brake dynamometers is demonstrated: the possibility to test brake together with a corresponding wheel, as intended to be required by some test procedures. This is particularly important from the point of view of a direct impact that a wheel may have to the brake heating/cooling capabilities.

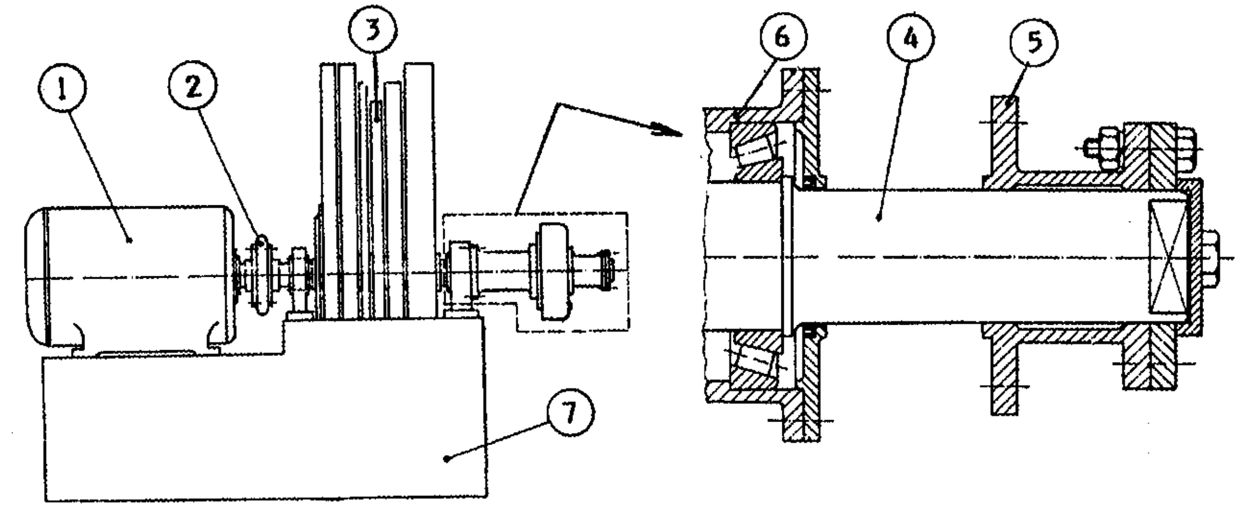



*Figure 5. The scheme of brake dynamometer PSK-20*

Both in the Figure 1 and in the scheme of Figure 5 an important feature of the LCBT brake dynamometers is demonstrated: the possibility to test brake together with a corresponding wheel, as intended to be required by some test procedures. This is particularly important from the point of view of a direct impact that a wheel may have to the brake heating/cooling capabilities.

The scheme in Figure 6. represents the full scale inertia dynamometer for laboratory testing of performance and reliability of oil immersed brakes and clutches PSS-51. This test stand consists of a massive support (1) carrying AC motor (2) to which the driving shaft (4) is connected via belt drive (3). The shaft (4) carries an energy accumulation flywheel (5). Besides, driving elements of an oil immersed friction clutch (6) are connected to it. Clutch plate (7) is connected to the driven shaft (8), which carries the brake plate (9) on one of its free ends, and the load flywheel (10) on the other. Stationary part of the brake (11) is connected to the support (1). Both clutch and brake are full scale mechanisms, comprised in the separate section of the test bench - housing (12) - which provides required conditions of oil delivery to the friction surfaces. Special hydraulic device that is not shown in the drawing enables oil circulation for renewal and cooling purposes. Inlet (13) is clutch control input, while inlet (14) is brake control input.

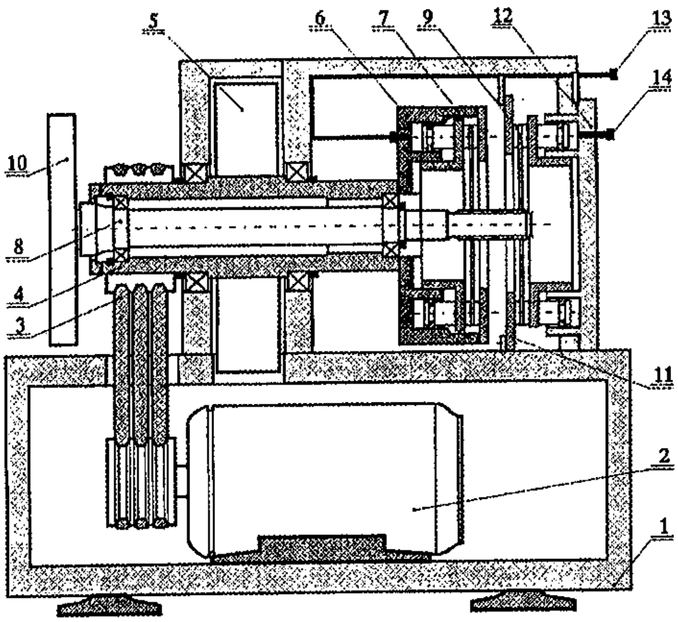


*Figure 6. Oil immersed brake and clutch dynamometer PSS-51*

This inertia dynamometer enables simultaneous testing of one oil immersed brake in association to one oil immersed clutch. Because driven parts of the clutch and rotating parts of the brake are connected via driven shaft, the clutch is tested in the "speed built-up" mode, while the brake is tested in the "braking" mode. It means that the cyclic test process is applied enabling the clutch to be engaged for driving and accelerating the load flywheel (11) from the rest to the motor speed. After this speed is attained, the clutch is disengaged, when the brake is actuated, bringing the load flywheel to the full stop. The test cycle is presented in Figure 7.

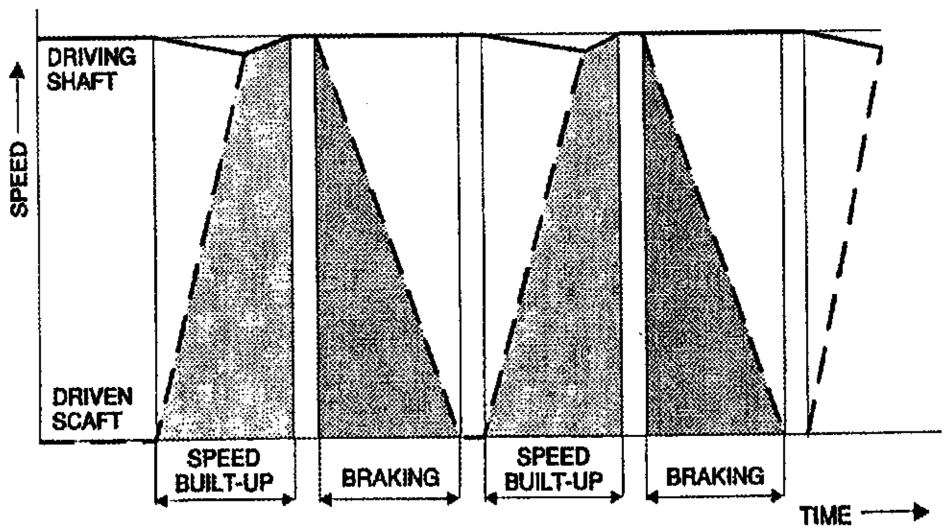


*Figure 7. Test cycle of the PSS-51 dynamometer*

The described concept for the test benches allows:
a) full scale brake and/or clutch application,
b) the rating performance evaluation of tested friction mechanism is enabled,
c) mechanisms of different types may be tested under appropriate load conditions,
d) identical mechanisms may be tested under different test modes,
e) highly rated duplication of real operating conditions is enabled,
f) automatic control and data processing enables a variety of possibilities to process and present test results and to evaluate tribological properties of the tested mechanisms.

All the inertia dynamometers developed at the Faculty of Mechanical Engineering in Belgrade are fully automated, providing automatic control of the test process and effective data acquisition, processing and presentation that is enabled by means of a full line of high performance electronically controlled devices and measuring equipment at the end of which a standard PC is used. The principle scheme of these important subsystems is explained in Figure 8 for PSS-51 rigs and in Figure 9 for PSK brake dynamometers.

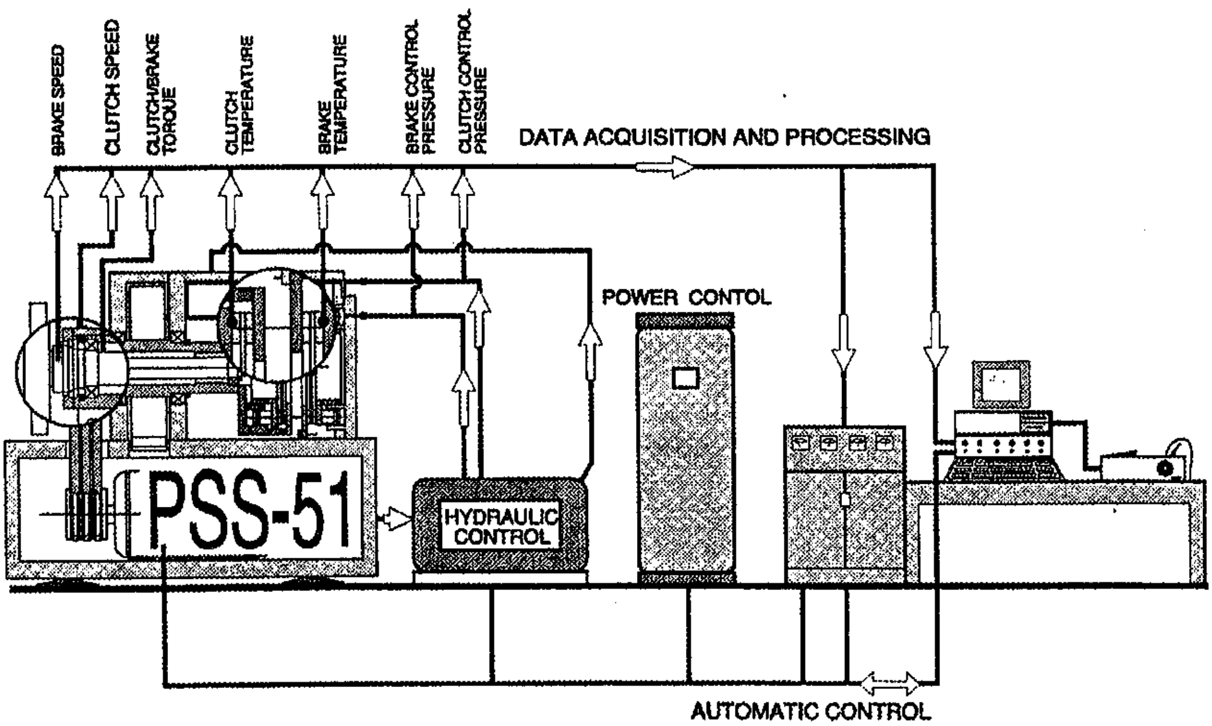



*Figure 8. PSS-51 dynamometer control and measuring system*

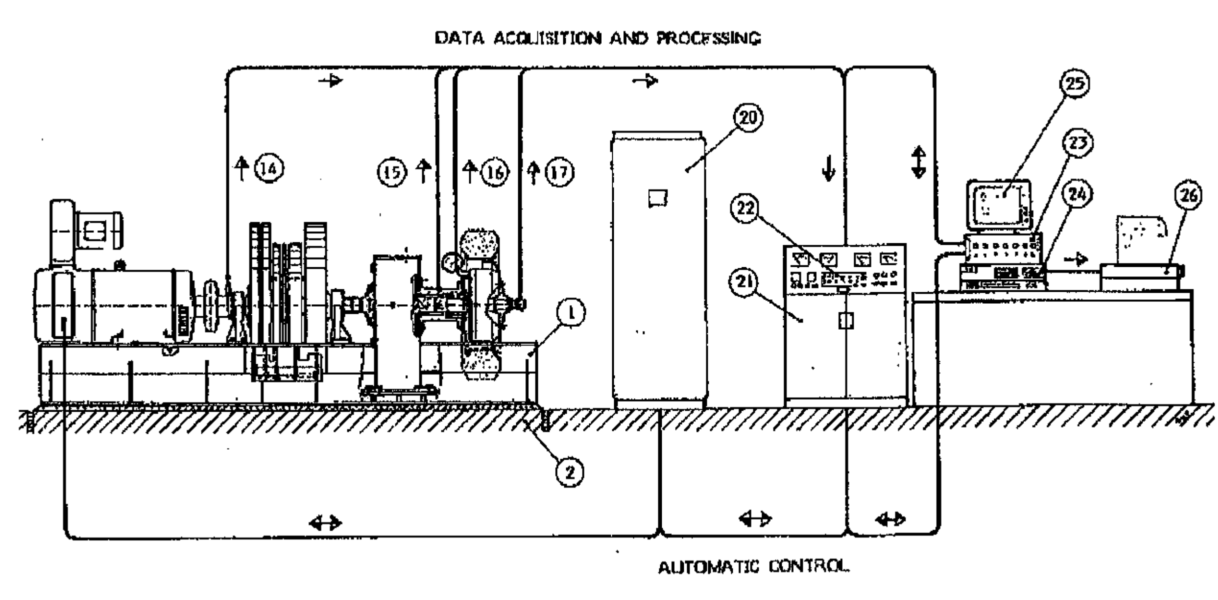



*Figure 9. Brake dynamometer's control and measuring system*

However, the control system also provides manual operation, enabling to the operator to decide when and how to activate the brake or other dynamometer functions (when to start motor, how to accelerate inertia flywheels, when to activate brake, etc.). By automatic mode, which is used practically in all test programs, especially for type approval testing, all control functions are overtaken by a microprocessor system. This system, as shown Figure 9, for example, comprises micro-computer with peripherals (24 to 26), data acquisition device (23), electronic measuring units (14 to 17), and the brake application and speed control device (20).

The automatic data processing is based on the "on-line" or "off-line" principle that comprises:
- acquisition of basic data, i.e. data obtained from the measurement of speed, number of drum/disc revolutions, air/hydraulic pressure, torque, brake interface temperature,
- data processing and

- presentation of the results.

Data processing is performed with help of corresponding software, developed so as to satisfy requirements or particular wishes. It is useful to note that the obtained results may be presented in different forms, as figures, tables or diagrams.

An example of a test report in the tabular form is shown in Figure 10, with all necessary explanations. This form of the test report relates to "standardised test procedure", developed also at the LCBT in Belgrade. It contains the identification data (tested brake, test program, number of test cycle) and obtained results (initial speed, braking torque, control line pressure, initial and final brake interface temperatures, work done by the tested brake for one or for a group of brake cycles, braking time and average deceleration).

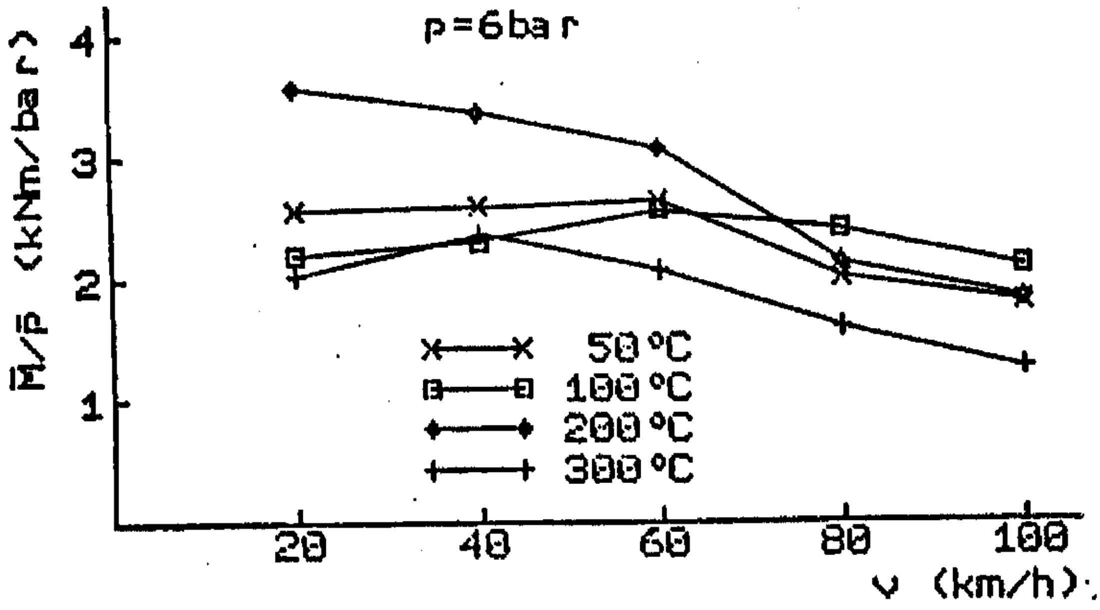
**DRUM BRAKE**

**TABLE 14 - SECTION 14-15**

| | NUMBER | INITIAL SPEED | TORQUE | LINE PRESSURE | TEMPERATURE INITIAL | TEMPERATURE FINAL | WORK | STOP TIME | DECELERATION |
|---|---|---|---|---|---|---|---|---|---|
| | [-] | [km/h] | [daNm] | [bar] | [C] | [C] | [J] | [sec] | [m/s^2] |
| SECTION 14 | 1 | 59 | 899.5 | 2.73 | 236 | 257 | 552338 | 4 | 5.33 |
| | 2 | 59 | 844.4 | 2.25 | 253 | 224 | 613052 | 4.4 | 5.06 |
| | 3 | 59 | 811.5 | 2.88 | 324 | 290 | 646225 | 4.7 | 4.36 |
| | 4 | 59 | 792 | 2.39 | 302 | 293 | 629331 | 4.8 | 4.69 |
| | 5 | 59 | 807.9 | 3.02 | 273 | 303 | 633015 | 4.7 | 4.84 |
| | 6 | 59 | 759.7 | 3.07 | 290 | 301 | 637340 | 5 | 4.35 |
| | 7 | 59 | 759.2 | 3.19 | 301 | 301 | 646564 | 5 | 4.55 |
| | 9 | 59 | 770.7 | 3.25 | 307 | 320 | 646531 | 4.9 | 4.62 |
| | 9 | 59 | 745.7 | 3.23 | 307 | 326 | 636677 | 5 | 4.47 |
| | 10 | 59 | 745.9 | 3.34 | 353 | 324 | 646910 | 5 | 4.59 |
| | 11 | 59 | 734.8 | 3.49 | 323 | 355 | 661314 | 4.9 | 4.7 |
| | 12 | 59 | 772.1 | 3.5 | 333 | 370 | 648432 | 4.8 | 4.75 |
| | 13 | 59 | 795.3 | 2.64 | 354 | 390 | 646122 | 4.8 | 4.77 |
| | 14 | 59 | 836 | 3.39 | 353 | 410 | 690199 | 4.7 | 5.01 |
| | 15 | 59 | 847 | 3.36 | 356 | 421 | 642467 | 4.5 | 5.09 |
| | 16 | 59 | 843.4 | 3.36 | 356 | 444 | 643737 | 4.5 | 5.07 |
| | 17 | 59 | 843.4 | 3.35 | 359 | 443 | 647574 | 4.5 | 5.39 |
| | 18 | 59 | 837.7 | 3.39 | 389 | 443 | 661567 | 4.6 | 5.32 |
| | 19 | 59 | 842.3 | 3.34 | 389 | 445 | 644805 | 4.5 | 5.05 |
| | 20 | 59 | 837.5 | 3.34 | 393 | 459 | 641116 | 4.6 | 5.02 |
| SECTION 15 | 21 | 59 | 935.7 | 3.75 | 335 | 426 | 617079 | 4 | 5.61 |
| | 22 | 59 | 930.3 | 3.29 | 300 | 387 | 427473 | 3.4 | 5.58 |
| | 23 | 59 | 813.6 | 2.78 | 287 | 392 | 633779 | 4.6 | 4.71 |
| | 24 | 59 | 862 | 2.92 | 335 | 376 | 633061 | 4.4 | 5.17 |
| | 25 | 59 | 857.9 | 2.73 | 253 | 375 | 634123 | 4.4 | 5.15 |
| | 26 | 59 | 877.5 | 2.77 | 252 | 372 | 639699 | 4.3 | 5.27 |
| | 27 | 59 | 873.1 | 2.73 | 238 | 359 | 602736 | 4.2 | 5.23 |
| | 28 | 59 | 842.5 | 2.95 | 237 | 356 | 631503 | 4.5 | 5.05 |
| | 29 | 59 | 852.3 | 2.96 | 224 | 359 | 623279 | 4.4 | 5.11 |
| | 30 | 59 | 837.8 | 2.34 | 221 | 352 | 636478 | 4.5 | 5.03 |
| | 31 | 59 | 850.2 | 2.32 | 218 | 336 | 580676 | 4.3 | 5.1 |
| | 32 | 59 | 852.2 | 2.35 | 206 | 326 | 626471 | 4.4 | 5.11 |
| | 33 | 59 | 840.4 | 2.37 | 256 | 303 | 607432 | 4.4 | 5.04 |
| | 34 | 59 | 873 | 2.72 | 255 | 206 | 562683 | 4.1 | 5.23 |
| | 35 | 59 | 835.2 | 2.73 | 154 | 289 | 623027 | 4.5 | 5.01 |
| | 36 | 59 | 854.2 | 2.32 | 131 | 292 | 614492 | 4.4 | 5.12 |
| | 37 | 59 | 811.2 | 2.64 | 137 | 253 | 583052 | 4.2 | 4.86 |
| | 38 | 59 | 784.7 | 2.75 | 131 | 256 | 627934 | 4.8 | 4.7 |
| | 39 | 59 | 757.2 | 2.67 | 118 | 218 | 510912 | 4.5 | 4.54 |
| | 40 | 59 | 765.4 | 2.76 | 105 | 223 | 622968 | 4.9 | 4.59 |
| | 41 | 59 | 730.1 | 2.72 | 119 | 219 | 626792 | 5 | 4.38 |

*Figure 10. Table of the test results*

Test results are often presented in the form of graphs or diagrams, as well. Some typical examples of the curves and graphs are shown in Figures 11. and 12, respectively, for a commercial vehicle drum brake tests. Upper diagram in Figure 11 shows the average brake torque (M) over mean control line pressure (p) for initial brake speed (v) from 20 to 100 km/h, obtained with constant control line pressure of 6 bar and with four different initial interface temperatures (50, 100, 200 and 300°C). Lower diagram in Figure 11. shows the average braking torque (M) with respect to control line pressure (p), for constant speed of 80 km/h and the same temperature levels as above.



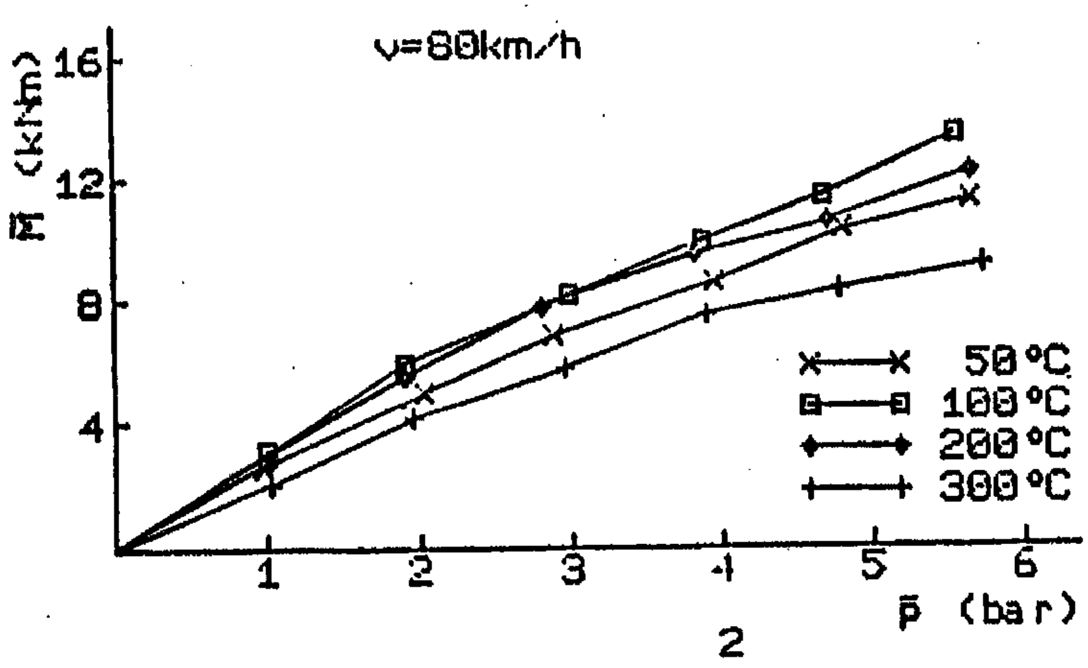




*Figure 11. Braking torque presentation over initial test conditions*

Diagrams in Figure 12. show the variation of braking torque (M) and control line pressure (p) during a number of consecutive braking cycles, realised with constant temperature (Θ) and constant speed (v), respectively. These and similar diagrams give possibilities for comprehensive and detailed analysis of the braking process, pointing out the most important influences and their effects.

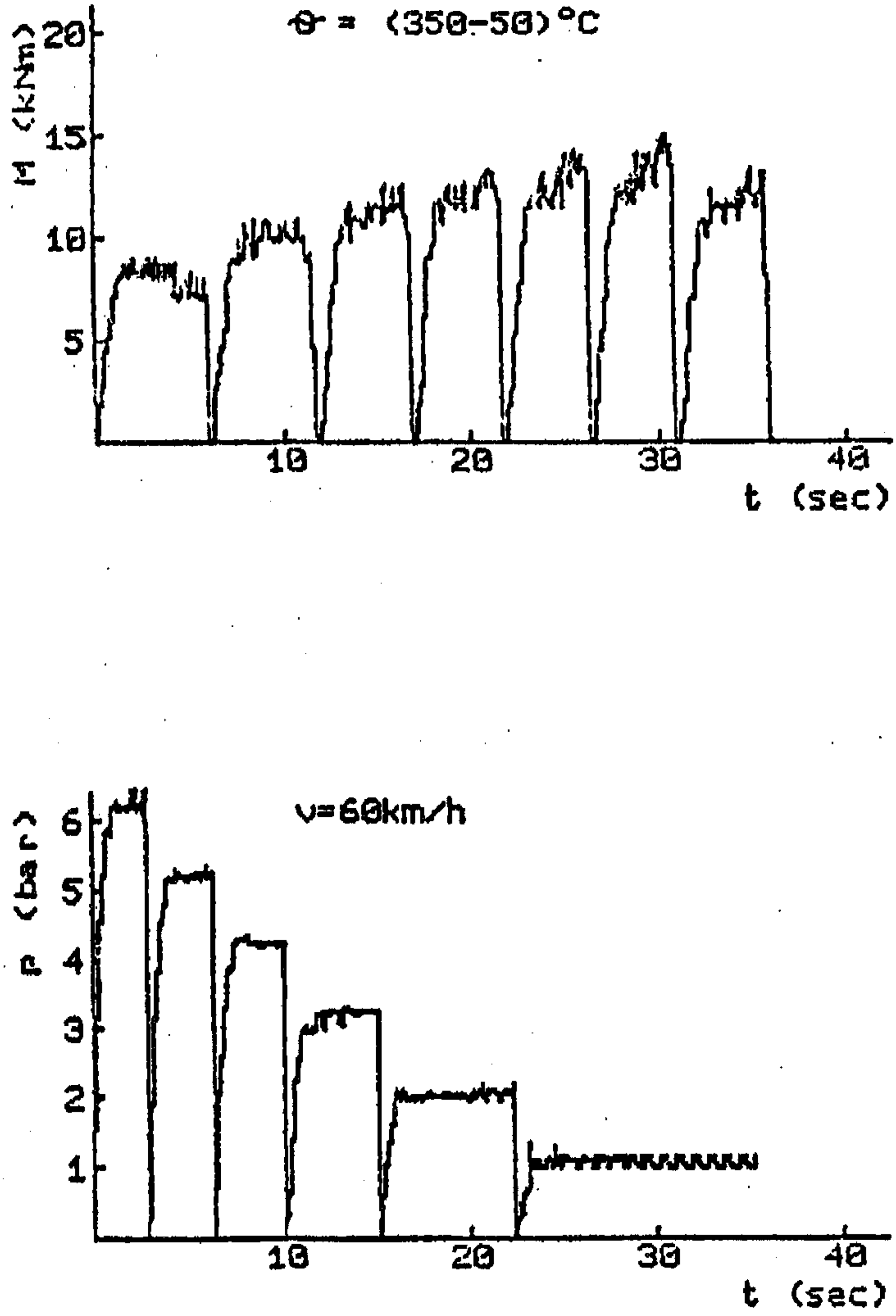



*Figure 12. Braking torque behaviour during brake application*

## 4. TEST PROCEDURES

In general, inertia dynamometers are used for experimental evaluation of tribological properties (friction and wear) of brakes, clutches and other types of friction mechanisms, as it is required by type approval or safety regulations. In many cases, however, results obtained by dynamometer testing make a basis for comprehensive research and investigation projects, including development of new products and new or improved materials used in friction mechanisms.

The following application of inertia dynamometers deserves a particular attention:

- Testing for certification or type approval purposes of friction mechanisms (like brakes in the case of heavy trailers) and/or friction materials intended for application in brakes and clutches as original equipment or spare parts (linings, pads, facings),

- Testing for quality control of brakes and/or other friction mechanisms in the series production, comprising conformity of production checks,

- Development testing of brakes and clutches, for different vehicle types and categories (new design or design modification), and in particular testing of asbestos and non-asbestos friction materials (new composition, improved technology),

- Research testing, especially related to the investigation of tribological phenomenon in brakes and clutches, like fade characteristics, wear mechanisms etc.,

- Development of improved test procedures and test facilities, including development of new or modification of the existing inertia dynamometers.

There are different test programs used by the industry or relevant independent test authorities to enable evaluation of tribological properties of friction brakes by means of application of an inertia dynamometer. Irrespective of the aim of brake testing, test programs normally comprise a number of general and/or specific issues, like bedding procedure, cold and/or hot performance tests, fade and recovery tests, wear tests etc. However, there are significant differences between test programs used by different test authorities over the world. A lot of work has been done within ISO or ECE, for example, to develop and introduce in practice some standardised test programs for evaluation of tribological properties of friction brakes, but still there are test programs applied by the individual test authorities following their own experience and philosophy of testing. That is why repeatability of test conditions and/or test results may become impossible even if the same friction mechanism is tested by two different test authorities, when each of them applies its own test program.

Because of that, the basic principle applied in LCBT with respect to test programs is to provide conditions for application of such a test procedure which would meet specific needs of the customer. That is why standardised test procedures following the ECE or ISO philosophy are applied in addition to test procedures prescribed by large vehicle manufacturers (like Mercedes-Benz or FIAT, for example, [19, 20]). However, own test programs are also developed to enable more detailed investigation of particular issues, like bedding procedure [6], wear test for life prediction [2, 5], modelling of tribological properties of friction materials (friction, wear, work done by the brake) [1, 14, 15, 16], tribo-mutation effects [8], quality control and inspection formally prescribed by Yugoslav standards, comprehensive investigations of friction materials wear mechanisms with particular emphasise on the possible environmental contamination [14, 16], braking force distribution optimisation [17], brake load and stress distribution analysis by comparison of finite elements theoretical models and inertia dynamometer test results [4, 12], or maintenance aspects of the brake wear process [7].

## 5. CONCLUSIONS

Almost thirty years of own experience and the intend of regulatory authorities to enlarge application of inertia dynamometer tests for certification, type approval, conformity of production and quality control purposes gives evidence that such a laboratory equipment is extremely suitable for experimental evaluation of brakes and other friction mechanisms. When supported by an appropriate automatic control and effective and sophisticated software for data acquisition, processing and presentation, inertia dynamometer testing provides results and information of the greatest importance for all aspect of tribology engineering in the field of friction mechanisms and materials, as well as for research and investigation of a variety of typically tribological phenomenon. That is why further expansion of application of such test equipment is foreseen to be highly appreciated.