

On Similarities and Differences of Measurements on Inertia Dynamometer and Scale Testing Tribometer for Friction Coefficient Evaluation

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ABSTRACT

Inertia dynamometers are commonly used to determine the friction coefficient of brake assemblies. Dynamometers are a well-established platform, allow testing under controlled conditions, exhibit a good correlation to many situations encountered in real driving, and are comparatively economical and less time-consuming than full vehicle test. On the other side of the spectrum is the use of scaled tribometer. These test systems make possible a test without the entire brake corner. This separation allows the investigation of the frictional-contact only (frictional boundary layer) speedily and independently of a given brake system or vehicle configuration. As the two test systems (inertia dynamometers and tribometers) may have different users with possibly different tasks, the question remains regarding how comparable the two systems are. These issues provide incentives to better define the fields of investigations, correlation, and applicability for the two systems.

In order to provide further insights and learning on this topic, this paper focuses on the measurement of the friction coefficient and the wear behavior using inertia dynamometer and scaled pin-on-disc tribometer testing. Thus, friction coefficient levels and sensitivity are investigated on both systems when using a tribometer based test sequence (test with constant speed) as well as using a standard inertia dynamometer test procedure (with dynamic braking with in-stop deceleration). Different types of lining-materials (e.g. low-met or OES, and NAO or RE) are tested and compared.

One major difference between the two systems is the energy input and thus the different temperature regimes. Therefore the influence of the initial temperature is a critical item the paper focuses on.

Lastly, the paper presents potential areas for integration with the objective of improving the overall correlation between the two methods and the ability to use a scale tribometer to predict full inertia dynamometer results for friction and wear evaluations during the product life-cycle.

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INTRODUCTION

The friction couple and its characteristic performance in brakes is determined mainly using inertia dynamometer testing with multiple international standards and corporate procedures. Typical dynamometer testing allows the isolation of the brake corner using only the friction couple and the vehicle caliper to apply the clamping force to mimic vehicle conditions.

Unfortunately, this can compromise the ability to use a given set of test results to support multiple product, manufacturing, or business decisions without multiple variations in the test setup.

Recent investigations on the possibility of reducing the multiples effects from size, geometry, and hardware from the measurement loop, provide the possibility of computing the friction coefficient with a more direct and simple measurement chain. To accomplish this, appropriate laboratory tribometers which allows a determination of the tribological characteristics are needed. These test systems make possible a test without the entirely brake system. This separation allows the investigation of the nearly pure frictional-contact (frictional boundary layer) speedily and independently of many disturbing influences.

In principle the question of the comparability of these two measurement systems arises. But even the question arises as to what is desired to measure: e.g. the performance and the realistic response of brake system or the friction and behavior of a brake-pad/disc-contact. Therefore this work focuses on similarities and differences of measurements on inertia dynamometer and scale testing tribometer for friction coefficient evaluation.

TEST EQUIPMENT AND METHODOLOGY

To measure the friction and wear behavior a standard inertia dynamometer and a scaled pin-on-disc tribometer are used. This allows the measurement of friction coefficient using two different test sequences: one from the tribometer with constant speed (HLT-based) and another one from standard inertia dynamometer test procedure with dynamic braking with in-stop deceleration (Dyno-based). In addition, two materials were tested under each method and conducted twice on each system to assess repeatability of the test results.

HLT - Scaled System Test

The friction measurement on the scaled system was conducted on the High-Load-Tribometer (HLT) at the Institute of Dynamics and Vibrations (IDS), Technical University Braunschweig (see [Figure 1](#)). With this device normal loads between 0.1 N and 1 kN can be applied at rotating speeds of up to 2080 RPM. The friction force and the normal force are measured directly and near to the contacting surfaces by a three-component piezo force sensor. This minimizes disturbing influences and provides a high accuracy reading. To reach different initial disk temperatures the disk is heated using two hot air guns. A detailed description of the HLT can be found in [1] and [2].

The size of the friction material specimens is 10 mm × 10 mm. The temperature of the test specimen is measured 1 mm below the surface with a glued-in thermocouple. The test specimen is glued in a special carrier with locating pins and four screws to provide repeatable positioning in the tribometer and other measuring devices at the IDS; see [Figure 2](#).

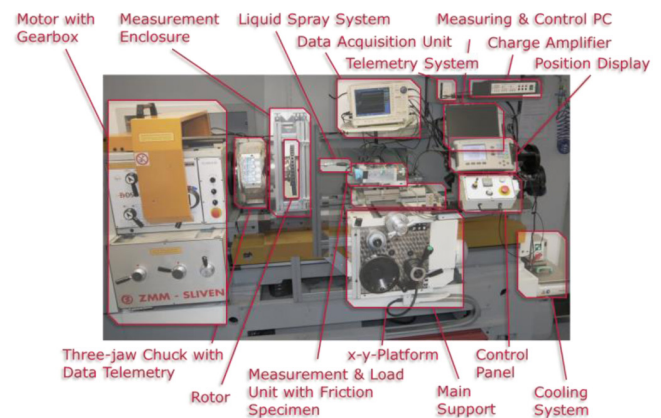


Figure 1. The IDS High-Load-Tribometer (HLT) at the Technical University Braunschweig

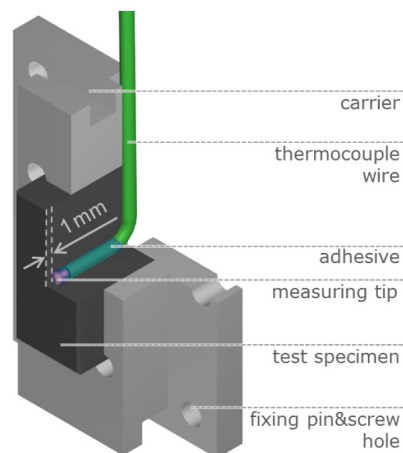


Figure 2. Test specimen with thermocouple, glued in a special carrier (schematic drawing)

The disc temperature is measured by thermocouples in the center of the rubbing trajectory 1 mm below the disc surface; see [Figure 3](#). The measured temperature signals are transmitted from the disc to the data acquisition unit by a telemetry system. The disc temperature is used as "initial brake temperature" (IBT) to commence the brake application.

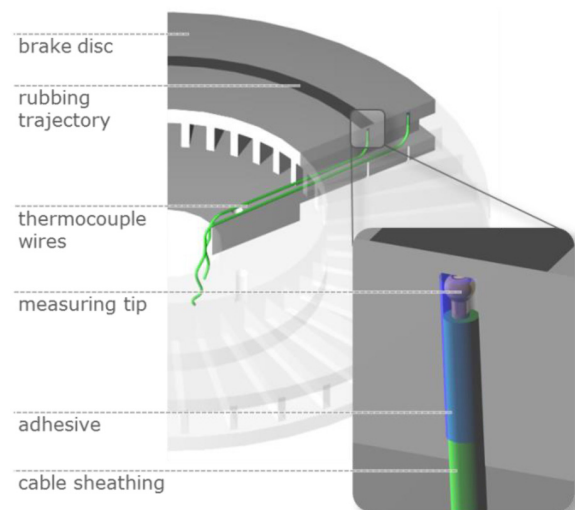


Figure 3. Disc temperature measurement with glued-in thermocouples (schematic drawing)

Scaling

To perform tests on the HLT emulating vehicle and brake conditions an appropriate scaling methodology is necessary. Otherwise, forces can become too large, increasing the driving power, and possibly requiring a physical inertia with undesirable interactions. In general the use of scaled laboratory tribometers, allows an easier separation of the different influencing factors and their interactions. These test devices make possible a test without the entire brake system. However, care must be taken to ensure the system is not severely reduced and the scaling remains physically meaningful; see [3] and [4].

Table 1. Symbols.

Parameter	symbol
Nominal surface pressure	$\hat{p}_{nom}, \hat{p}'_{nom}$
Vehicle speed	v
Area of nominal contact surface	A_{nom}, A'_{nom}
Scale factor	k_A, k_r
Brake pressure	$\hat{p}_B$
Piston area	A_{piston}
Normal force	F_{normal}, F'_{normal}
Rotating velocity	ω, ω'
Effective radius	r_{eff}, r'_{eff}
Rolling radius	$r_{rolling}$
Rotational speed	n
Relative velocity (at rubbing contact)	$\dot{x}', \dot{x}$
Duration of braking	t'_{brake}, t_{brake}
coefficient of friction	μ
inertia	I
deceleration (at rubbing contact)	$\ddot{x}, \ddot{x}'$

The first scaling requirement relates to the unit pressure on the friction surface so the mean (and constant) surface pressure in both systems, in the original and the scaled one ('), is equivalent: $\hat{p}'_{nom} == \hat{p}_{nom}$. The scaling of the normal force between one pad (also calculating only with nominal contact surface of one pad) and the disc is defined as:

$$\Rightarrow F'_{normal} = \frac{A'_{nom}}{A_{nom}} \cdot F_{normal} = \frac{A'_{nom}}{A_{nom}} \cdot \hat{p}_B \cdot A_{piston} \triangleq \frac{1}{k_A} \cdot \hat{p}_B \cdot A_{piston} \quad (1)$$

The second requirement pertains to providing the same relative velocity at the mean or effective rubbing surface $\dot{x}'(t) == \dot{x}(t)$. From this it follows Eq. (2) for the rotating velocity:

$$\Rightarrow \omega'(t) = \frac{r_{eff}}{r'_{eff}} \cdot \omega(t) \triangleq k_r \cdot \omega(t) \quad (2)$$

With this, the rotational speed to be set at the HLT by Eq. (3):

$$\Rightarrow n'(t) = k_r \cdot \frac{v(t)}{2\pi \cdot r_{rolling}} \quad (3)$$

The third requirement applies to providing the equivalent duration of the braking event with $t'_{brake} == t_{brake}$. For a known coefficient of friction μ , the deceleration at the mean or effective rubbing contact is defined by Eq. (4):

$$\Rightarrow \ddot{x}' = - \frac{2\hat{p}_B \cdot A_{piston} \cdot \mu}{I} \cdot \hat{r}_{eff}^2 \quad (4)$$

This results in equal energy dissipation per unit area, with the dissipated energy also scaled with the factor k_A . This scaling corresponds substantially to the Energy Density approach from WILSON, BELFORD and BOSHER [5].

After applying equations (1), (2), (3), (4) to the brake configuration and vehicle being simulated, the test conditions for the HLT are as described on Table 2.

Table 2. Scaling Parameters

Scaling parameter	Value
sample size (A'_{nom})	100 mm ²
pad surface size (A_{nom})	3016 mm ²
piston area	2856 mm ²
k_A	30.16
effective radius vehicle	107.9 mm
effective (center) radius HLT	131 mm & 120 mm
k_r	0.823 & 0.899
inertia	42.7 kg · m ²
rolling radius	290.0 mm

Dynamometer Test

All tests were performed on the same inertia dynamometer using the same test setup. The dynamometer tests were conducted on a Link dynamometer Model 3000, at its main test facility located at Link Engineering, Dearborn Technical Center in Michigan. Figure 4 illustrates a typical dynamometer equivalent to the one used for the tests.

For the brake discs, the thermocouple was installed at the center of the rubbing surface, 1 mm deep. For brake pads, the thermocouple was installed at a depth of 1 mm near the center of the friction surface.

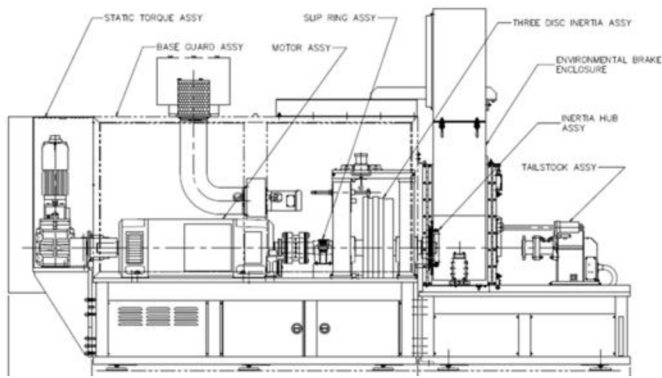


Figure 4. Illustration of the inertia dynamometer with a passenger car brake

Inertia-dynamometer testing, being more repeatable, reproducible, and cost-effective than vehicle testing, can also be subject to large variations in results if critical factors like hardware condition, cooling air, test parameters, and report templates are left unchecked [6, 7]. Hence, the following factors were ensured to be the same to test under repeatability conditions:

- Inertia-dynamometer
- Cooling air and orientation relative to the brake assembly
- Control program and test parameters
- Test report template
- OES rotor and caliper assemblies
- New rotor and pads for every test
- Testing staff

Materials and Test Procedures

Test parts are GMX380 front right brake discs (18041971) and OES brake pads (ACDelco 171-1092) as well as after-market replacement brake pads (BrakeBest D1160). The OES friction material is a low-met formulation; the replacement friction material is an NAO formulation.

Each test sequence was performed twice on each pad material: OES brake pads (called OE-material) and after-market replacement brake pads (called RE-material). For each test a new but equivalent disc was used. On the HLT also a new rubbing track is used for each test in order to reduce number of required parts. All tests (dynamometer and HLT) used new friction material or new coupons.

Dyno-Based Test Sequence

The dynamometer-based test procedure is an extract of the standard industry test procedure SAE J2522 (AK-Master-Test) [8]. The selected sections are 3, 4.1 - 4.3 and 5. All applications are with in-stop deceleration and starts with an initial brake temperature of 100°C. Only the run-in (burnish) differs by using constant speed and constant pressure on both systems. This is because of an easier handling on the HLT. A matrix of the dyno-based test sequence is shown in Table 3. To perform this

procedure on the HLT the deceleration levels are estimated prior to the test according to Eq. 4 and set via the HLT-motor speed control.

Table 3. Dyno-based Test Sequence

Section #	Section Description	# of Applies	Braking Speed km/h	Release Speed km/h	Cycle Time s	Pressure Level bar	Initial Temp. °C
W0	Initial Wear Measurement						
0	Run-in	100	80	80	10	30	100
W1	Post Run-in Wear Measurement						
1	Char. values	10	80	30	-	30	100
2	Speed/pressure I	8	40	5	-	10, 20, 30...80	100
3	Speed/pressure II	8	80	40	-	10, 20, 30...80	100
4	Speed/pressure III	8	120	80	-	10, 20, 30...80	100
5	Char. values	10	80	30	-	30	100
W2	Final Wear Measurement						

Tribometer-Based Test Sequence

The tribometer-based test procedure is derived from the dynamometer-based procedure. So, the same velocities (initial speed) and a similar pressure range are chosen. Different from the dynamometer, all applications are with constant speed and no deceleration. In addition, the initial temperature is 100°C and all applications are 10 seconds long. This HLT-based test sequence and its parameters are shown in Table 4.

Table 4. HLT-based Test Sequence

Section #	Section Description	# of Applies	Braking Speed km/h	Release Speed km/h	Cycle Time s	Pressure Level bar	Initial Temp. °C
W0	Initial Wear Measurement						
0	Run-in	100	80	80	10	30	100
W1	Post Run-in Wear Measurement						
1	Drag 1	20	40	40	10	30	100
2	Drag 2	20	80	80	10	30	100
3	Drag 3	20	120	120	10	30	100
4	Drag 4	20	80	80	10	30	100
5	Drag 5	20	80	80	10	60	100
6	Drag 6	20	80	80	10	10	100
7	Drag 7	20	80	80	10	30	100
W2	Final Wear Measurement						

Wear Measurement

The wear of the specimen extracted from the brake pads is measured using a fully automated measuring device, which provides nondestructive wear measurement. Thereby the distance between the sensor and the surface of the sample is measured repeatedly with a contactless laser, which operates according to the triangulation principle. From the change of the distance and the surface area the system provides a calculation of the volumetric wear of the sample.

This measurement method does not affect the surface of the pad, and can be used during a friction-measurement procedure. This system is highly sensitive and produces high-precision measurements. The control method minimizes operational errors and increases the measuring efficiency. For a more detailed description of this measurement device see [9].

The pad wear measurements for the dynamometer tests used a high-precision automated XY-table with lasers to locate the measurement point, and an LVDT with fixed preload to measure thickness. The rotor measurements use high-precision calipers as specified on inertia-dynamometer test method with a 0.001 mm resolution.

RESULTS

Repeatability (Test-to-Test Variation)

In order to assess the ability of the test systems to provide similar results in a consistent manner, an evaluation of the repeatability of the test results (dyno and HLT separately) is done. The data required to conduct such assessment was obtained by testing twice under each test procedure for each one of the two materials.

Repeatability on the HLT

From the test results using the inertia dynamometer-based test procedure the mean coefficient of friction from both repetitions is mostly within 0.02 with few differences. This is observed for both materials as shown in Figures 5 and 6.

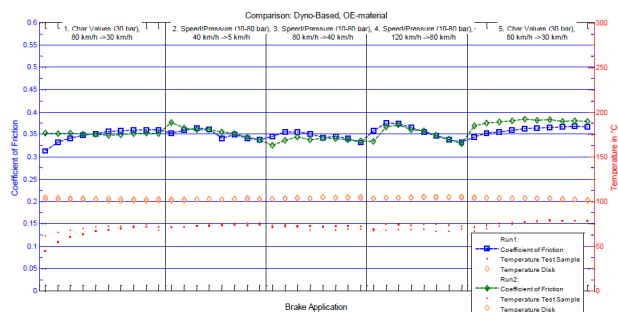


Figure 5. Mean coefficient of friction and temperatures on HLT for the dyno-based test procedure from two specimens of the OE-material.

Using the tribometer based (HLT-based) test sequence (with constant speed) slightly different results were observed. For the OE-material on Figure 7, the mean coefficients of friction from both test are also well within 0.02.

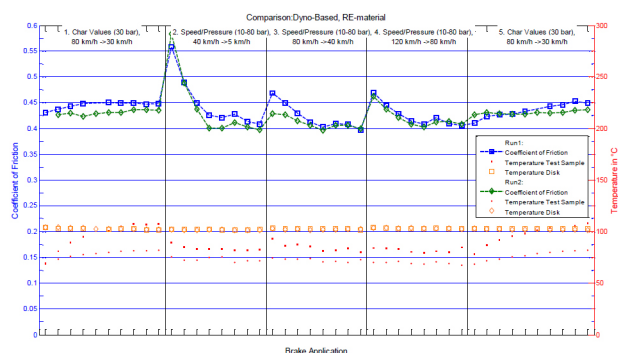


Figure 6. Mean coefficient of friction and temperatures on HLT for the dyno-based test procedure from two specimens of the RE-material.

On the opposite hand, the results from the two specimens of the RE-material are not as similar; see Figure 8. The first two sections (30 bar at 40 km/h and 30 bar at 80 km/h), and the second-to-last section (10 bar at 80 km/h) exhibited significant differences of the mean friction values.

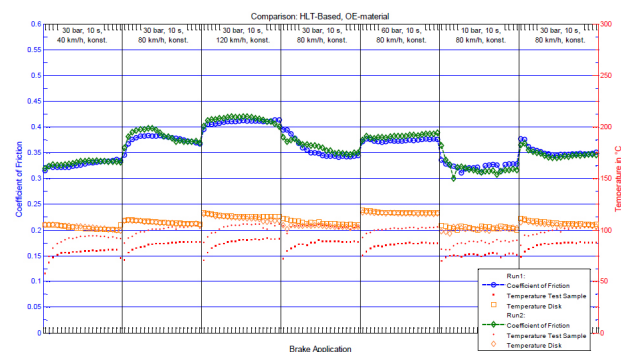


Figure 7. Mean coefficient of friction and temperatures on HLT for the HLT-based test procedure from two specimens of the OE-material

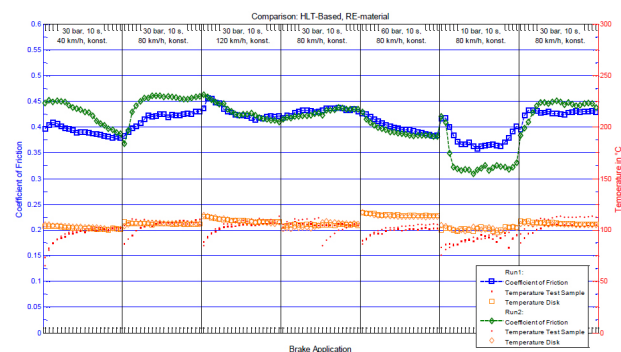


Figure 8. Mean coefficient of friction and temperatures on HLT for the HLT-based test procedure from two specimens of the RE-material

The statistical evaluation (paired-t hypothesis test for a mean difference of 0.02) with a p-value of 0.05 yields no significant differences on the HLT-based tests on the HLT system with the OE material; see Figure 9.

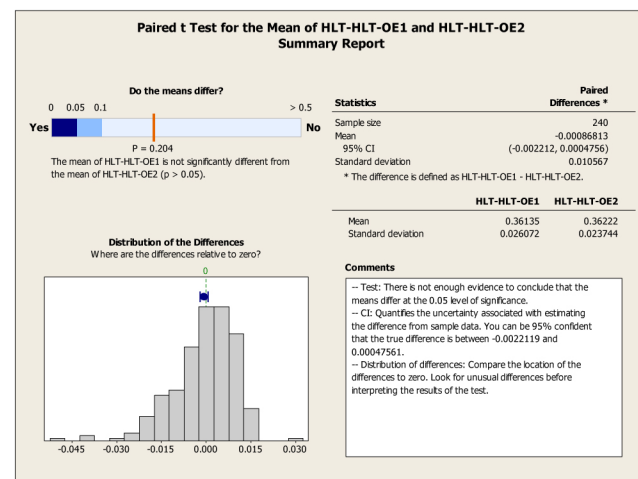


Figure 9. Paired-t test on HLT with HLT-based test on OE material