

Influence of Test Procedure on Friction Behavior and its Repeatability in Dynamometer Brake Performance Testing

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ABSTRACT

The efforts of the ISO "Test Variability Task Force" have been aimed at improving the understanding and at reducing brake dynamometer test variability during performance testing. In addition, dynamometer test results have been compared and correlated to vehicle testing.

Even though there is already a vast amount of anecdotal evidence confirming the fact that different procedures generate different friction coefficients on the same brake corner, the availability of supporting data to the industry has been elusive up to this point. To overcome this issue, this paper focuses on assessing friction levels, friction coefficient sensitivity, and repeatability under ECE, GB, ISO, JASO, and SAE laboratory friction evaluation tests. With multiple companies (or programs) developing and assessing the friction coefficient and friction behavior under different methods, it is inevitable to avoid conflicts of performance requirements or lack of reproducibility or correlation of test results under different test methods.

In order to provide an evaluation consistent with previous phases of the Task Force activities, the same brake corner assembly and same friction material is used for this study. The study is comprised of three main steps:

1. Conducting tests under several test procedures.
2. Assessing and comparing friction levels, in-stop friction behaviour, repeatability, as well as friction coefficient sensitivity to the test conditions, including the friction-couple thermal history.
3. Presenting benefits and limitations of each procedure as-written along with a simplified comparison of the test sequences and its main test conditions.

Similar to previous phases of the project, the study uses statistical tools for the multidimensional comparison.

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INTRODUCTION

Laboratory testing to determine the friction coefficient of a friction couple (friction material and its mating rotor or drum) or a given friction material on a standard mating surface is by far the most common test procedure conducted by the automotive brake industry. Therefore, understanding the similarities and differences among them is crucial to the entire supply-chain.

For this phase of the project, all dynamometer tests were conducted using the same dynamometer to test under repeatability conditions and reduce the test system contribution to test variability. The non-dyno test methods, using coupons extracted from the friction material used specific test systems as indicated in the test procedure.

PROJECT HISTORY

This phase of the ISO Test Variability task-force is the fifth project which spans five years of continuous work. The friction coefficient measurement and evaluation is a critical metric for the entire brake supply-chain to support key decisions such as:

- formulation design, raw materials selection, and manufacturing process conditions
- selection of friction material supplier along with the specific manufacturing site(s), and
- boundary conditions on the friction material which will determine other brake behavior such as NVH, durability, structural integrity, and physical properties.

Over time and as the result of the interaction of regional, business, and technical conditions, there is a large number of test procedures (including regulations, standards, and corporate or proprietary), multiple test systems designs, vintages, and providers, and multiple foundation brake types, designs, and sizes to suit different applications and needs.

Since part-to-part, test-to-test, dyno-to-dyno, and lab-to-lab variability are interconnected, the brake engineering community has been asking itself about the best method to assess the expected level of test variation, how to better quantify it using industry-approved methods and tools, and how to reduce it in a systematic and economical way [1]. Thus far, the ISO task force has completed four phases:

- Phase 1: accuracy study involving one method, five dynamometers, and two tests on each to quantify repeatability, reproducibility and to detect potential sources of variation [2] using ISO statistical methods [3], and industry-accepted software tools and methods [4].
- Phase 2: Design of Experiments to assess main effects of critical factors based on the sources of variability and the

deviations from reproducibility conditions by some of the laboratories during the phase 1 of the project [5].

- Phase 3: documenting findings and potential enhancements to international test standards using the ISO 26867 method as an example [6]. Some elements and findings from this phase were already implemented during the revision of the SAE J2521 noise squeal test procedure [7].
- Phase 4: Vehicle-to-dyno correlation using a common vehicle-based test procedure. This phase also used a DOE approach and exhibited better repeatability and correlation on the front brakes v. the test brakes [8].

Due to the logistics, and the engineering resources associated with this project, only one brake design and size and one friction material have been used for all the phases of the project. Hence, the reader needs to exercise caution when applying the finding of this project on other testing activities, especially when using numerical ranges or numerical values indicated on the different papers previously published. Secondly, the industry is challenged to develop and allocate resources to conduct similar projects using other test procedures, different friction materials, and testing on different brake designs.

TEST SYSTEM SELECTION, TEST PROCEDURES, AND TEST PARTS

In order to characterize the friction coefficient levels, repeatability and correspondence to other methods, the test procedures selected reflects the following categories (a) full inertia-dynamometer using vehicle-specific test conditions and test hardware, and deceleration-type of braking during the test (b) inertia-dynamometer using vehicle-specific test hardware and brake applications at constant speed during the test(s), and (c) special-purpose test systems at constant speed rubbing the sample (coupon) against a drum or a disc of known and standard configuration and specifications.

Test system selection

Different test procedures use a different layout, different type of sample (out-of-the-box pads, single coupon, or double coupon) and mating component (vehicle brake disc, standard drum, or standard disc) as a function of the type of test. See [Figure 1](#). The figure also depicts an illustration of the actual test system. Zimmer [9] provides a valuable summary and a brief history of the evolution of test systems covering Dynamometer, Chase Link, FAST, Ranzi Cuna, Ranzi LCR, and the Friction test machine from ATE.

The inertia-dynamometer used for the dynamic braking tests (using corner assemblies) was selected in order to ensure a broad range of testing capabilities and able to accommodate all the test conditions required by the different test methods used for the project. The main specifications of the inertia-dynamometer used are the following:

- Test inertia (prior to inertia simulation): 200 kg·m²
- Torque: 5600 N·m
- Brake pressure: 21 0000 kPa
- Rotational speed: 2000 RPM
- Brake temperature: 1300°C
- Full environmental control for cooling air temperature and relative humidity at the brake

For the coupon test procedures (SAE J661 and GB5763), the specific procedure determines the features and full-scales required.

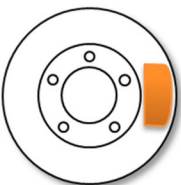
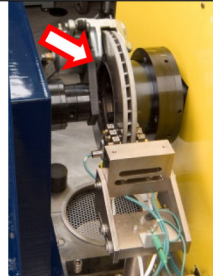
Inertia-dynamometer	Special-purpose test system	
SAE J2521, J2522, and J2784 ECE R90-A3, -A9 ISO 26867, JASO C406	SAE J661	GB 5763
		
		

Figure 1. Test system, specimen type, and number of specimens as a function of the test procedure. Inertia-dynamometer tests use two pads (inner and outer) per test. The orange shapes indicate the specimen type and location. The orange arrows indicate the location of the specimen relative to the mating surface

Test Procedure and Test Specimen Selection

The process to select the test procedures to conduct as part of this phase of the project was straightforward. As the objective was to provide an evaluation of friction coefficient under different test methods around the world per publicly-available procedures, a search of the different international standards commonly used (or mandated as part of a given regulation or requirement) yielded a list comprised of three groups: (a)

inertia-dynamometer tests with deceleration braking, (b) inertia-dynamometer test with drag braking, and (c) coupon testing also using drag braking.

Inertia Dynamometer Test Procedures using Deceleration Braking

Different laboratory friction material characterization methods have been developed over the last decades worldwide with commonalities and also with differences which do not allow a simple and straightforward comparison to other methods. Being the most common laboratory test for friction coefficient characterization, the following international standards using a full brake corner assembly and vehicle-specific test conditions were used. Depending upon the test procedure, two, three, or ten repeats were performed to quantify test repeatability.

ISO 26867: 2009 - Road Vehicles - Friction Behaviour Assessment for Automotive Brake Systems [10].

This test method was developed as part of the industry-wide effort culminated on the ISO 15484 [11] for quality assurance of disc and drum friction materials for passenger cars and commercial vehicles. The ISO friction behavior test is a cost-effective dynamometer test to support development, benchmarking, and product monitoring which also provides the key metrics indicated on the ECE R90 annex 9 [12] for nominal coefficient of friction, minimum coefficient of friction, and maximum coefficient of friction as part of the Conformity of Production process. This procedure was conducted on two samples.

SAE 2522:2013 Dynamometer Global Brake Effectiveness Procedure [13].

developed originally in Europe as the AK Master in the late 1990s by the AK Working Group. It has become a common test procedure to determine the sensitivity of the friction material to changes in braking speed, brake pressure or deceleration, initial brake temperature, and thermal history. It is also the basis for several vehicle manufacturers, tier-1 brake suppliers, and tier-2 friction manufacturers. This procedure was conducted on two samples.

SAE 2521:2013 Disc and Drum Brake Dynamometer Squeal Noise Test Procedure.

This test procedure was originally developed by the European Working Group as the AK Noise. In addition to becoming the de-facto standard test procedure to assess the noise propensity of brake assemblies above a threshold of 70 dB(A) in the 1.25 kHz to 16 kHz range; it includes several friction characterization sections useful in assessing the friction level under constant pressure along the test sequence. All squeal noise matrixes above 5 bar also report the average friction coefficient. Because of the significant differences with other test methods, sections using brake drag applications were run to ensure proper lining conditioning and brake work history, but are not included in the comparisons for friction coefficient. This procedure was conducted on two samples.

SAE 2784: 2009 FMVSS Inertia Dynamometer Test

Procedure for Vehicles Below 4540 GVWR [14]. Developed also as part of the industry discussions for the ISO 15484, this single-ended inertia dynamometer procedure replicates the vehicle test sequence using vehicle loading, inertia levels, and deceleration levels mandated by the actual vehicle test sequence or typically observed on the test track. The SAE J2784 also includes the test sequence mandated by the FMVSS 105 for vehicles between 3500 kg and 4540 kg of Gross Vehicle Weight Rating. Test results from this procedure, when combined with the appropriate vehicle information and reference torque output from the non-tested axle, can be used to predict vehicle performance related to stopping distance. This procedure was conducted on two samples.

JASO 406:2000 Passenger car - Braking device -

Dynamometer test procedures [15]. Developed following the main sequence of the FMVSS 105 vehicle test, it allows the quantification of torque output and friction coefficient for passenger cars under normal and failed conditions, at different load levels, and includes a water baseline and recovery section at the end of the test. The braking speeds during the test are a function of the maximum vehicle speed. This test method allows three possible test setups (a) single-ended using a single brake corner assembly, (b) front-to-rear dual-ended, or (c) right-to-left dual-ended. This project used single-ended testing to make it comparable to the other inertia-dynamometer tests. In addition, and different from the other dynamometer tests, the JASO C406 uses the lining temperature (fixed side) to control the initial brake temperature. This procedure was conducted on two samples.

ECE 90-02:2013 Uniform Provisions concerning the approval of replacement brake lining assemblies, drum brake lining and discs and rums for power-driven vehicles and their trailers - Annex 3: item 2.2. This item on the European regulation establishes a uniform method to assess friction coefficient during cold effectiveness testing and speed sensitivity using single-ended inertia-dynamometer testing. The latest revision of the dynamometer test incorporates a burnish sequence using the structure and logic of the SAE J2522 and the ISO 26867 test procedures. This procedure was conducted on two samples.

Inertia Dynamometer Test Procedures using Drag Braking

ECE 90-02:2013 Uniform Provisions concerning the approval of replacement brake lining assemblies, drum brake lining and discs and rums for power-driven vehicles and their trailers - Annex 9; Part A; item 2.2. The regulation, which is based on the VDA 285-1 specification [16] uses torque control and pressure control. The origins of this method dates back to the late 1960s as a development from Alfred Teves as the ATE Friction Test Machine using a 90 minute test cycle. It is customary to conduct torque controlled brake applications for new brake systems, while pressure controlled brake

applications are reserved for vehicles manufactured prior to 1996. This project used the latter to compare to pressure controlled braking on the SAE J2522 and the ISO 26867. This project conducted three repetitions of the test. This procedure was conducted on three samples.

Scale (Coupon) Testing using Drag Braking**SAE J661:2013 Brake Lining Quality Control Test**

Procedure [17]. Developed into a SAE Recommended Practice in the mid-60s, this procedure uses a (25.4 × 25.4) mm coupon rubbing at a constant speed and constant normal force against a cast iron drum which resembles a typical brake drum casting. In order to achieve the target temperatures and times during the test, the system relies on a blower-heating system. For the brake size used on this project, the test conditions equivalent to the vehicle equated to moderate braking speeds and brake pressures during city traffic. This procedure is currently used mainly to support quality control activities and for formal certification for friction materials for a nominal friction level at normal and hot conditions per the SAE J866 [16], not for product development purposes or to predict vehicle-level behavior. It also supports the product registration to demonstrate compliance to the heavy metals limits enacted by the states of California [18] and Washington [19] in the United States and effective January 1st 2014 and January 1st 2015, respectively. During this project six tests total were conducted; three on the inner pad and three on the outer pad. It is interesting to note the fact that both sets of data produced different edge codes at elevated temperatures.

GB 5763:2008 Brake Lining for Automobiles; item 5.3 [20].

Developed in the late 1990s following the JIS 4XXX [21], this test procedure runs using two (25 × 25) mm samples running in parallel along the same rubbing track on a standard disc and with the test load applied by dead weights. The GB5763 specification establishes both, friction level and friction level variability as well as wear rates. In order to quantify the inner and the outer pad behavior separately, coupons from fives pads were conducted on the inner and five pads on the outer pads.

Deceleration v. Drag Braking

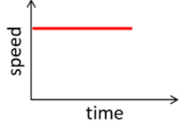
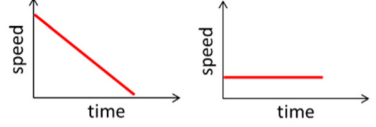
Different test procedures use different methods to control the brake during the friction coefficient measurement cycle. Except for the ECE R90 drag friction tests (and the drag modules of the SAE J2521), all dynamometer tests use a deceleration cycle where the torque output from the brake decelerates the inertia discs and motor assembly. Table 1 illustrates the method to control speed for the different procedures. It is worth noting the fact the SAE J2521 uses drag speeds of 3km/h and 10 km/h, opposed to the ECE R90-A6, GB5763, and the SAE J661 which relies on dragging speeds equivalent to approximately 70 km/h (for the brake and tire size on this project) on the vehicle to generate the same linear speed at the friction couple interface.



Documents

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Table 1. Speed control by test procedure

Test procedure	Speed control during braking
ECE R90-A3 ISO 26867 JASO C406 SAE J2522 SAE J2784	
ECE R90-A9 GB 5763 SAE J661	
SAE J2521	

Selection of Key Procedure Sections for Friction Coefficient Comparison

In order to analyze and compare test procedures several key sections were defined. Friction material is sensitive to load history or sequence of modules. Even an identical module in a different position will lead to different friction behaviour. Figure 2 shows the key sections in the respective test procedure sequence.

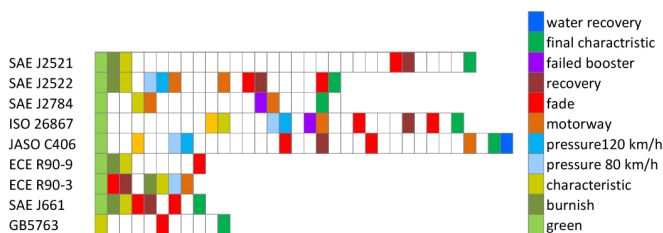


Figure 2. Sequence of key sections under each test procedure

Standard inertia-dynamometer test procedures conduct a large number of different braking conditions to increase the efficiency of the test and with repetition of certain modules to assess the effects of load history.

SPECIFIC DIFFERENCES BETWEEN PROCEDURES AND SECTIONS

Some of the specific differences between test procedures and their sections are:

- Overall kinetic energy dissipated and test duration
- Overall arrangement of sections
- Inertia level and inertia changes (during SAE J2784 and JASO C406) to reflect different loading conditions
- Evaluation of brake applications and extraction of key figures from test procedures
- Burnish sections with a variety of: number of brake applications, constant versus changing energy and power, initial brake temperature with some tests (like ISO 26867) at elevated temperatures to save test time, and intentionally incomplete burnish to monitor the evolution (like SAE 2521)

- Temperatures during fade modules: coupon at or around 350°C; full scale dynamometer test at or around 550°C
- Test procedures with predominantly lower pressures show higher friction levels (SAE 2521; SAE 661; GB 5783)

Table 2 (a), (b), (c) summarize test set-up, test conditions and other important information for all procedures.

Table 2. Test set-up test conditions, and non-friction metrics for each test procedure

(a)

	number of sections	total application	total duration / hour	total energy / kWh	burnish application	burnish duration / hour
SAE J2521	31	2377	37.8	32.2	32	1.3
SAE J2522	20	404	15	23.9	192	6.6
SAE J2784	19	287	14.5	22	200	8.9
ISO 26867	30	364	8.2	20.2	192	3.8
JASO C406	34	625	21.6	33.2	200	5.1
ECE R90 A9	9	130	2.3	4.9	50	1.3
ECE R90 A3	8	181	9.5	11.6	64	3.1
SAE J661	8	154	2.4	3.5	20 min	0.4
GB5763	11	3750	3.5	7.6	95% contact	-

(b)

	test system	test setup	type of braking	Environmental control	total wear rotor / g	total pad wear / g
SAE J2521	dynamometer	full size	decal / drag	25 °C / 50 %RH	14.8	17.2
SAE J2522	dynamometer	full size	decel	fresh air	6.8	17.9
SAE J2784	dynamometer	full size	decel	25 °C / 50 %RH	6.5	15.4
ISO 26867	dynamometer	full size	decel	20 °C / 50 %RH	5.3	20.9
JASO C406	dynamometer	full size	decel	fresh air	8.8	20.2
ECE R90 A9	dynamometer	full size	drag	fresh air	2.5	5.2
ECE R90 A3	dynamometer	full size	decel	fresh air	4.8	8.8
SAE J661	friction tester	coupon	drag	fresh air	n.a.	0.8
GB5763	friction tester	coupon	drag	fresh air	n.a.	1.3

(c)

	Min. braking speed / km/h	Max. braking speed / km/h	Min. brake pressure bar	Max. brake pressure bar	Min. initial rotor temp. / °C	Max. initial rotor temp. / °C
SAE J2521	3	100	0	51	-8	546
SAE J2522	40	195	10	80	38	550
SAE J2784	50	156	25	103	34	500
ISO 26867	20	200	0	120	25	553
JASO C406	50	160	7	128	19	532
ECE R90 A9	76	76	18	18	24	377
ECE R90 A3	75	160	15	56	25	480
SAE J661	44	59	12	8	35	315
GB5763	75	75	5	16	68	357