

Brake Dynamometer Test Variability Part 2- Description of the Influencing Factors

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ABSTRACT

The ISO TC22/SWG2 - Brake Lining Committee established a task force to determine and analyze root causes for variability during dynamometer brake performance testing. SAE paper 2010-01-1697 "Brake Dynamometer Test Variability - Analysis of Root Causes" [1] presents the findings from the phases 1 and 2 of the "Test Variability Project." The task force was created to address the issue of test variability and to establish possible ways to improve test-to-test and lab-to-lab correlation.

This paper presents the findings from phase 3 of this effort-description of factors influencing test variability based on DOE study. This phase concentrated on both qualitative and quantitative description of the factors influencing friction coefficient measurements during dynamometer testing. The Design of Experiments investigated factors regarding: *brake cooling, environmental conditions* during testing, *kinetic energy level, pad soak* prior to testing, *location of control temperature, caliper drag* condition, and number of snubs in the burnish section.

The paper describes a methodology used to select the levels for the factors used during the study, and possible ranges of factor variations encountered during actual testing. The ranking of factors by their importance to reduce test variability is determined based on the effect on variation of the friction coefficient metrics (and other metrics related to test execution) defined on the ISO 26867 test procedure [2].

The findings and conclusions, even though are specific to the boundary conditions and the brake configuration used for this DOE study, are useful for further refinement of existing test procedures, laboratory test equipment, test results evaluation, and testing conditions with the primary aim of reducing test-to-test and lab-to-lab variability during regular testing activities.

SUMMARY OF THE VARIABILITY PROJECT-PHASES 1 AND 2

This collaborative accuracy study using the ISO 26867 test involved five brake inertia dynamometers located at five different test facilities. The evaluation of the results combined traditional and statistical methods (Six-sigma and ISO Statistical Methods [3,4,5]).



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From the initial findings, the most significant sources of test result variability were:

- Brake cooling conditions
- Temperature measurement technique
- Algorithms to calculate friction coefficient
- Interpretation of test procedure
- Execution of test procedure

The findings from the first two phases of the project had more of a qualitative nature with limited ability to quantify the influences from a single factor isolated from its potential interactions with others.

IDEA BEHIND VARIABILITY PROJECT-PHASE 3

The aim of the third phase of the project was to confirm the findings from the first and second phases of the study by a qualitative and quantitative description of the factors influencing friction coefficient measurements during dynamometer testing. The findings from this phase are useful to establish guidelines to update current brake performance test specifications. The control of some influencing factors can be more complex and expensive to address compared to others. One factor widely discussed is the environmental conditioning of cooling air. Many dynamometers currently installed are not equipped with such climate control systems - and the updates are expensive and technically demanding. This study addressed brake performance testing conducted on brake dynamometers; however, the findings are also valid for other brake test areas like NVH.

Because of the vast field of possible sources of variability, this paper does not attempt to provide specific answers to all the questions rising from the findings or to explain the tribology mechanisms behind the different friction behavior observed during testing - those answers leave room for further investigations and refinements.

THE DOE PRINCIPLE AND SELECTION OF APPROPRIATE DOE METHOD

For the detection and description of the importance of the different individual factors, the task force used a Design of Experiment method. This method for planning experiments determines (quantifies) the forced changes of test output while controlling varying influencing factors. Two aspects determine the definition of the DOE in general, which have a direct influence on the quality of results and number of test runs: DOE resolution number of factors, and limits (or levels) of influencing factors under investigation. These items and decisions have a direct influence on the quality of the results and the number of test runs.

FACTORS AND THEIR LIMITS

The number of factors for this phase was reduced to a reasonable minimum, seven, for eight runs (tests) total. The identification of influencing factors from 2008 was refined in 2010 [6]. From the initially 52 factors influencing test-to-test and dyno-to-dyno variability, the task force selected seven factors with potential to affect test results variability as shown in [Table 1](#). Further reduction on the number of factors could reduce the overall value of the study.

During DOE studies, for better identification of the effects of the limits, the low and high level for each factor represent extreme but realistic values. For this study four factors used numerical limits, one factor used attribute categories (thermocouple location for controlling the initial brake temperature, lining vs. rotor), and two factors used combinations of numerical limits or hardware setup (*brake cooling and kinetic energy* level). [Table 1](#) summarizes the seven DOE factors with their limits (low and high levels).

[Table 2](#) indicates the run order and the combinations used during the actual tests.

Factor A-*brake cooling* is a combination of three parameters: airflow amount, orientation of incoming air relative to the caliper clock position, and distance from the cooling air discharge to the outside diameter of the rotor as shown in [Figure 1](#).

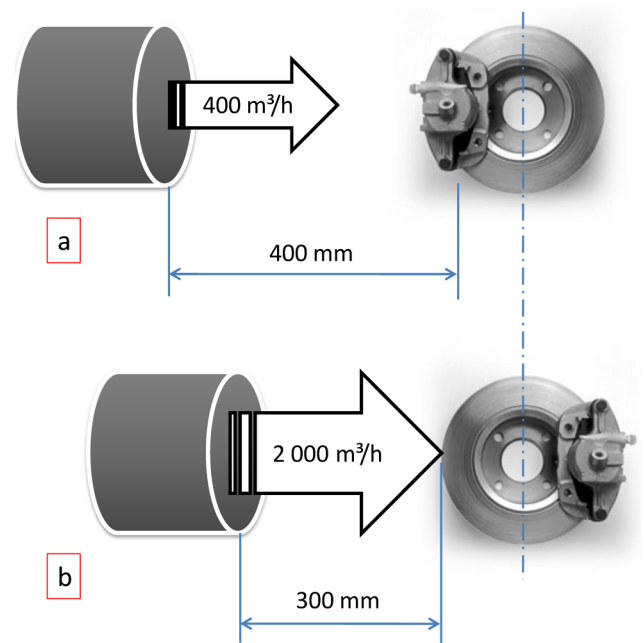


Figure 1. Levels for factor A. (a) low brake cooling. (b) high brake cooling

Table 1. Description of the seven factor and its limits

Factor	Factor Name	Low	High	Remarks
A	Brake Cooling	400 m³/h; Incoming air onto caliper; 400 mm from rotor outside diameter	2 000 m³/h; Incoming air opposite to caliper; 300 mm from rotor outside diameter	horizontal airflow combining: airflow amount, caliper orientation relative to incoming cooling air , and distance from the duct exit to the outside diameter of the rotor
B	Environmental Conditions	(5 ± 2) °C at (50 ± 5) % RH cold/dry	(30 ± 2) °C at (80 ± 5) % RH hot/humid	Calculated absolute humidity: Cold/dry – 3.4 g/m³ Hot/humid – 24.4 g/m³
C	Kinetic Energy Level	90 % inertia 95 % braking speed	110 % inertia 105 % braking speed	Combination of test inertia and test speeds (braking and release) for all brake applications to provide ± 21 % kinetic energy from the nominal conditions
D	Pad Soak	(5 ± 2) °C at (40 ± 5) % RH cold/dry	(30 ± 2) °C at (95 ± 5) % RH hot/humid	Soaking for 24 hours under climate conditions of test
E	Thermocouple Location	Lining TC	Rotor TC	two common control methods for dyno testing with thermocouple at nominal depth and position per ISO 26867
F	Caliper Drag	Zero drag	High drag	using preload springs to generate high drag (nominal 10 N·m) and spreading springs for the zero drag
G	Burnish Cycles	32 snubs	192 snubs	minimum and maximum number of snubs per ISO 26867

Table 2. Run order and factor combinations for each test

Run	Brake cooling	Environmental conditions	Energy level	Pad soaking	Temperature control	Caliper condition	Burnish cycles
1	2000 m³/h	5 °C / 50 %RH	90%I & 95%V	5 °C / 40 %RH	Lining TC	Zero drag	192 snubs
2	2000 m³/h	5 °C / 50 %RH	110%I & 105%V	5 °C / 40 %RH	Rotor TC	High drag	32 snubs
3	400 m³/h	5 °C / 50 %RH	110%I & 105%V	30 °C / 95 %RH	Lining TC	High drag	192 snubs
4	400 m³/h	5 °C / 50 %RH	90%I & 95%V	30 °C / 95 %RH	Rotor TC	Zero drag	32 snubs
5	400 m³/h	30 °C / 80 %RH	110%I & 105%V	5 °C / 40 %RH	Lining TC	Zero drag	32 snubs
6	400 m³/h	30 °C / 80 %RH	90%I & 95%V	5 °C / 40 %RH	Rotor TC	High drag	192 snubs
7	2000 m³/h	30 °C / 80 %RH	90%I & 95%V	30 °C / 95 %RH	Lining TC	High drag	32 snubs
8	2000 m³/h	30 °C / 80 %RH	110%I & 105%V	30 °C / 95 %RH	Rotor TC	Zero drag	192 snubs

Factor C-Energy level is a combination of the two parameters that determine the total kinetic energy during braking: test inertia and rotational speed as shown in Eq. 1 and 2 for low and high level respectively.

$$KE_{low} = \frac{1}{2} (0.9 \cdot I) \cdot [(0.95 \cdot \omega_i)^2 - (0.95 \cdot \omega_f)^2] \quad (1)$$

Where KE is total kinetic energy, I is the total test inertia, ω_i is the initial angular speed, and ω_f is the final (release) angular speed for a given brake application.

$$KE_{high} = \frac{1}{2} (1.1 \cdot I) \cdot [(1.05 \cdot \omega_i)^2 - (1.05 \cdot \omega_f)^2] \quad (2)$$

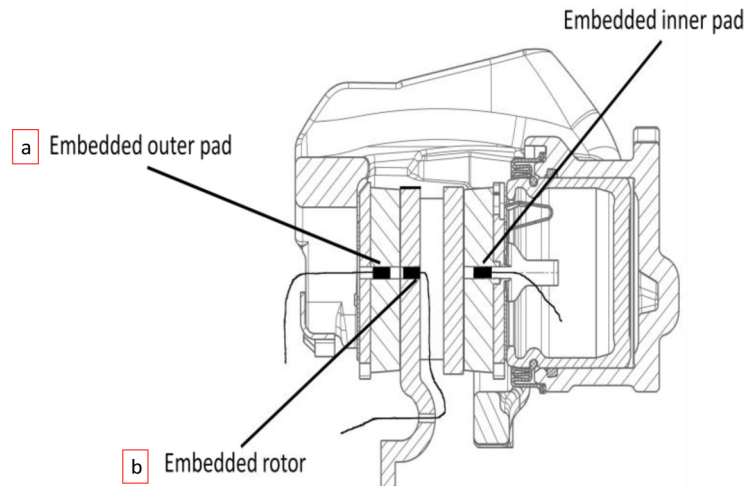


Figure 2. Levels for factor E. (a) lining temperature control. (b) rotor temperature control

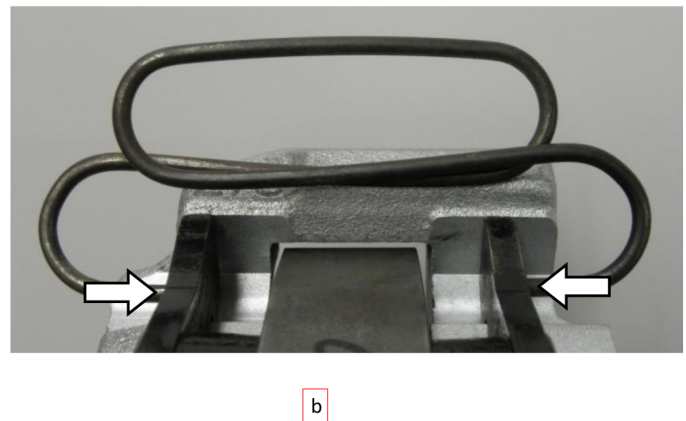
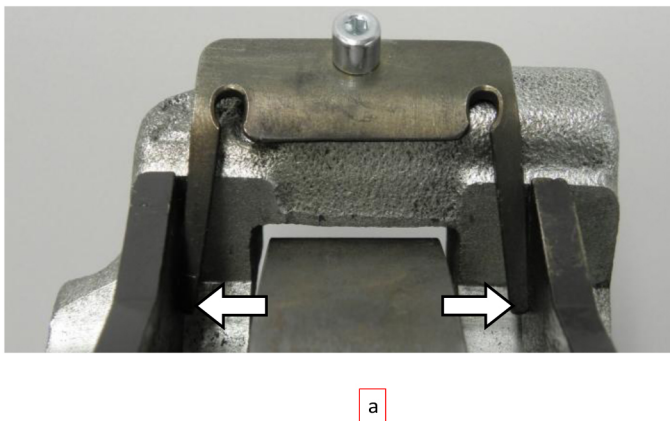


Figure 3. Levels for factor F. (a) zero drag caliper. (b) high drag caliper. The arrows indicate the direction in which the spring force is applied to the inboard and outboard pads

Factor E -*Temperature control* uses lining or rotor to control the initial brake temperature as shown in [Figure 2](#).

Factor F-*Caliper drag* uses two sets of special purpose springs to provide high drag and zero drag during the tests. The high drag spring provides a nominal preload of (80-100) N and generates a drag torque of approximately (6.5-9) N·m. The zero drag spring Design slightly pushed back the pads away from the rotor to avoid brake drag. [Figure 3](#) illustrates the two spring configurations. From physical observation of the spring behavior during testing, the low, zero drag spring did not perform correctly its spreading function during all tests. This condition is equivalent to production calipers, which typically exhibit a drag level significantly lower than the drag imposed with the high drag springs.

Factors B, C, D and G are commented directly in [Table 1](#) and do not require additional explanation.

DOE RESOLUTION

The confidence level of the DOE study results depends on the so-called DOE resolution. The resolution of the experiment describes the complexity of the design and interactions. A better DOE resolution (more runs) will have a trade-off with the project duration, total costs, and the amount of resources required. In general, there are three types of DOE studies, which are performed for one of the following reasons: screening (lowest resolution), modeling (average resolution) and optimization (highest resolution). In order to avoid any confounding among the test factors, the full-factorial DOE design is very popular. They allow conclusions not only about the influence from all factors, but also about the influence of interactions among them [7]. The three options to design the DOE provide the following configurations:

- Full-factorial DOE: $2^7 = 128$ runs with no interactions
- Resolution IV or higher = 2^4 to $2^6 = 16$ to 124 runs allowing investigation of interactions



Table 3. Single values from initial fingerprinting

<i>Parameter</i>	<i>Run 1</i>	<i>Run 2</i>	<i>Run 3</i>	<i>Run 4</i>	<i>Run 5</i>	<i>Run 6</i>	<i>Run 7</i>	<i>Run 8</i>
Piston moving pressure (bar)	0.6	0.56	0.54	0.56	0.42	0.52	0.46	0.59
Dynamic efficiency (%)	98.1	97.7	98.0	97.9	97.3	97.7	97.4	97.2
Rollback clearance after 2 MPa (20 bar) (mm)	0.16	0.23	0.3	0.21	0.29	0.31	0.19	0.15
Rollback clearance after 6 MPa (60 bar) (mm)	0.14	0.22	0.29	0.24	0.28	0.3	0.18	0.16
Sliding force (N)	70	73	84	72	88	58	85	78

• Resolution III = 2^3 runs typically used for screening and provides a more efficient test resource utilization. This resolution level is more challenging to assess thru the DOE results. This study uses a two-level, resolution III DOE

TESTING

TEST PROCEDURE SELECTION

Similar to the first two phases of the project, the ISO 26867 Friction Behavior Assessment for Automotive Brake Systems test procedure [2] was used for this study. The ISO 26867 combines a wide range of brake application types (controlled by pressure or deceleration), initial brake temperature, braking conditions (braking and release speed, pressure or deceleration levels, and brake temperature), and has common sections with other well known and accepted performance and NVH dynamometer test procedures [1]. In addition, the test duration allowed the logistics to set up, execute, and tear down the test within 24 hours, which was determined by the pad soak cycle.

SAMPLE PREPARATION

Brake rotors were from the same batch selected for lowest variability regarding lateral Run-out (LRO), Disc Thickness Variation (DTV), and first natural frequency. Low steel brake pads were from series production, the inner and outer brake pads came respectively from the same production batch, and all pads were selected for lowest between-sample compressibility variation [1].

Rotors and pads were prepared following the settings and instructions on the ISO 26867 procedure regarding thermocouple location and depth, thickness measurements, and total weight. In addition, a sliding thermocouple was set up on the same friction surface as the embedded (control thermocouple per the DOE plan) and at nearly the same radial location. All the temperature measurements on the rotor were on the outboard friction surface. Prior to testing (per the DOE

schedule), the brake pads were soaked at the appropriate temperature and humidity on two separate environmental chambers (one at each setting per the DOE matrix) for at least 24 hours.

CALIPER FINGERPRINTING

Since eight unique calipers were required for this study, an initial evaluation determined if it was necessary to evaluate the possible level of influence from the caliper onto the results of the ISO 26867 test. That included the determination of the respective piston moving pressure as well as dynamic efficiency, which were required to calculate the friction coefficient correctly. Table 3 illustrates the values measured for each caliper using special purpose spacers.

The values for rollback with spare spacers, piston moving pressure, and sliding force measured on a test bench for quasi-static measurements were within specifications with no significant impact on caliper behavior during the tests. The dynamic efficiency measurement was obtained on the dynamometer with extra linings after 60 burnish stops prior to the DOE runs.

All the friction coefficient calculations use the average values of 50 kPa (0.5 bar) for threshold pressure and 98% for caliper efficiency.

DYNAMOMETER SELECTION AND PREPARATION

The dynamometer used to perform all the testing was one of the five used during Phase 1 of the project (accuracy study for repeatability and reproducibility). The dynamometer has the following main specifications:

- 200 kg·m² of mechanical inertia plus inertia simulation
- 5,600 N·m of torque
- 20 MPa (200 bar) of hydraulic pressure

- Semi anechoic walk-in brake chamber
- Noise recording capabilities
- Variable cooling air speed (or airflow) and adjustable orientation relative to the brake
- Flexible air duct with a diameter of 254 mm
- Environmental conditioning for air temperature and humidity (relative or absolute)
- Brake temperature measurement with non-rotating thermocouples (embedded on brake pads, rotor sliding, and rotor infrared), and rotating thermocouples (embedded on brake rotor)
- Fully-programmable with automatic data collection set to 1 kHz

In preparation for the testing, the air speed (discharge velocity) was adjusted to be equivalent to the two airflows specified in the DOE matrix for low and high cooling of 400 m³/h and 2,000 m³/h, respectively. Since the airflow is not uniform across the duct section, the average of 13 measuring locations was used following a simplified Log-Chebyshev method defined on ISO 3966:2008 [8]. This model uses a velocity distribution law as a function of the distance from the wall, logarithmic in the outermost elements of the section and polynomial in the other elements. As the weighting coefficients are equal, the air speed (discharge velocity) is equal to the arithmetic mean of the measured local velocities. [Figure 4](#) shows the positions for the discharge velocity measurement and [Figure 5](#) shows the actual measurements for both airflow levels.

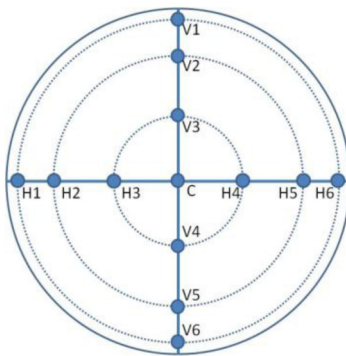


Figure 4. Measurement locations per simplified Log-Chebyshev method

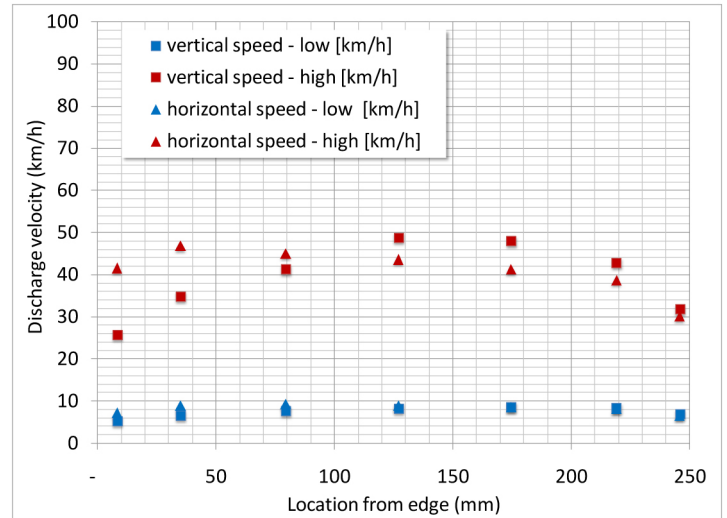


Figure 5. Discharge velocities in both directions per simplified Log-Chebyshev method

TESTING

Testing did not have interruptions, used the same brake fixture (Level 1 using a rigid knuckle assembly with hub, rotor, and caliper bracket), and had the same team of test technicians and test engineers for the entire testing. The tests followed the sequence:

1. Caliper quasi-static measurements for pre-selection
2. Caliper dynamic efficiency testing on 11 candidate calipers to select a set of eight
3. Statistical evaluation of dynamic efficiency tests for: piston moving pressure, dynamic efficiency, rollback clearance after 2 MPa (20 bar) and after 6 MPa (60 bar), and sliding force
4. Shake-down of test procedure (verification) for proper sequence and servo-controller tuning
5. Execution of test matrix per [Table 2](#) above with wear measurement at the end of each test

Some tests took longer than anticipated due to the combined effects of *brake cooling*, *environmental conditions*, and *caliper drag*. The entire test execution was approximately one week as all the tests were commenced with the appropriate level of staffing present, and the time between tests was mandated by the pad soaking of 24 hours.

TEST RESULTS

DOE EVALUATION

The evaluation of test results uses three types of assessment: general friction results comparing average friction coefficients from all brake applications from all tests;

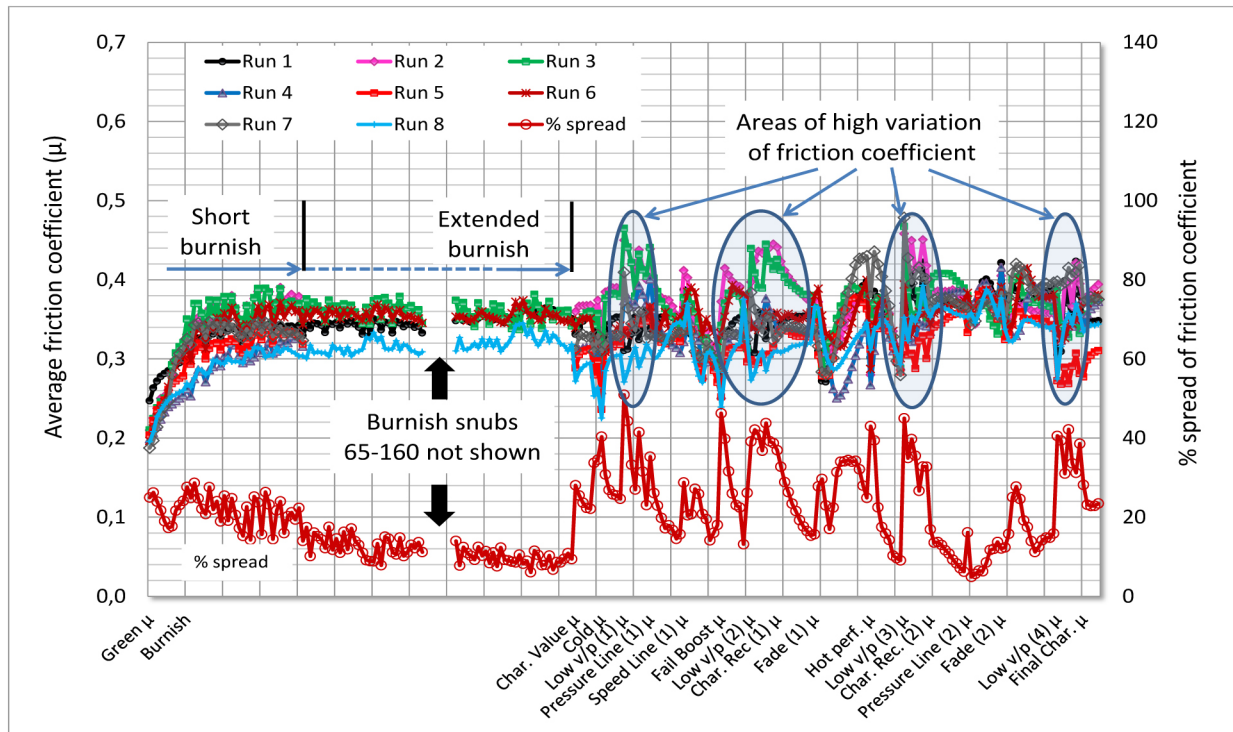


Figure 6. Average-by-distance friction coefficient during the ISO procedure. Elliptical callouts (burnish snubs, cold μ , boost fail, and low speed/low pressure sections) indicate the test sections, which exhibited the largest variation (range of up to 50% of the average for all runs combined). Burnish cycles 3-5 are not shown

statistical assessment using Six-sigma methodologies for main effects, interaction plots; and hypothesis testing to detect significant differences.

General Friction Results

Figure 6 shows calculated average-by-distance friction coefficients during the ISO procedure runs. The entire test sequence includes 20 sequential sections. As shown in Table 2, the DOE runs differentiated by number of burnish snubs (32 or 192 for low and high burnish cycles respectively).

Six-Sigma Statistical Evaluation

The evaluation of the results from the DOE investigation uses the methods and statistical parameters (Alpha-value = 0.05) as defined in Minitab [7]. The assessment includes three types of evaluations:

- Main effects and Pareto charts for the each factor to assess significant effects
- Interaction plots among the seven factors when compared pair wise along with two-way normal analysis of means to assess significant interactions
- Pareto charts (grouped by factor) of the effects on all the metrics specified on the ISO 26867

Main Effects for Average Friction Coefficient

Test **average** friction level in ISO 26867 is specified as “average friction value from all brake applications from steps:

3 -Characteristic value; 5-(Cold) characteristic section, last 5 stops; 7-Pressure line (1); 8-Speed line (1);

12 -Characteristic/recovery (1); 16 -Characteristic/recovery (2); 17 -Pressure line (2); and 20 -Final characteristic, all without optional brake applications.”

Figure 7 indicates that *caliper drag* and *environmental conditions* have the largest effect on the variation of the average friction coefficient, and both factors are statistically different from the other factors. High *caliper drag* (additional clamping force on the pads), and cold / dry environmental conditions (faster cooling of transfer layer due probably to a higher temperature gradient enhancing the dissipation rate, and less ambient humidity hence providing less “lubricant effect” on the transfer layer) produce higher friction coefficients on average. It is interesting to note the relatively small effect from *brake cooling*, *thermocouple location*, and *kinetic energy*, which would be “intuitive” sources of friction coefficient variation.

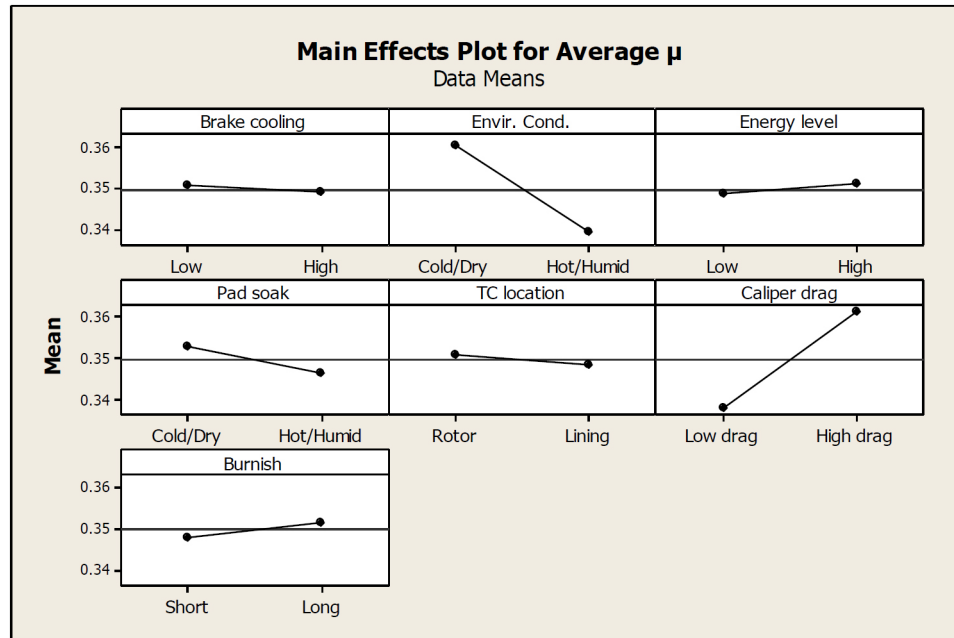


Figure 7. Main effects on average friction coefficient (μ) as a function of each of the seven factors

Main Effects for Minimum Friction Coefficient

Test **minimum** friction level in ISO 26867 is specified as “minimum friction value from all brake applications from steps:

3 -Characteristic value; 5-(Cold) characteristic section, last 5 stops; 7-Pressure line (1); 8-Speed line (1);

12 -Characteristic/recovery (1); 16 -Characteristic/recovery (2); 17 -Pressure line (2); and 20 -Final characteristic, all without optional brake applications.”

Figure 8 shows that the factor that exhibits the largest influence on the overall minimum friction coefficient is the *caliper drag* (similar to the overall average friction coefficient). No factor produces a statistically different effect but excessive *caliper drag* (coming from a worn-out caliper with a long history of testing, from poor workmanship during manufacturing, or permanent damage from excessive loading) can skew the test results and induce variability near or at the limit of acceptable test-to-test variation. Other factors like *pad soak* and *energy level*, have an effect of approximately 50% of the *caliper drag* effect. In addition, except for the *burnish* cycles, all other factors (besides *caliper drag*) exhibit a tendency to lower the friction coefficient for hot / humid environment, high energy level, hot / humid pad soak, and lining temperature control. The latter factor level generates higher temperatures at the transfer layer.

Main Effects for Maximum Friction Coefficient

Test **maximum** friction level in ISO 26867 is specified as “maximum friction value from all brake applications from steps:

3 -Characteristic value; 5-(Cold) characteristic section, last 5 stops; 7-Pressure line (1); 8-Speed line (1);

12 -Characteristic/recovery (1); 16 -Characteristic/recovery (2); 17 -Pressure line (2); and 20 -Final characteristic, all without optional brake applications.”

Figure 9 shows that *environmental conditions*, *energy level*, and *caliper drag* are factors with a significant effect on the maximum friction coefficient variation. Commonly, the maximum friction coefficient occurs during mild-to-low energy brake applications where other factors or brake characteristics could have a more significant effect. Such factors or characteristics could be transfer layer conditioning (influenced by the *environmental conditions*); external loading which increases the apparent friction coefficient (influenced by high *caliper drag*); and in-stop thermal loading (influenced by the *energy level* and dependent upon the friction formulation behavior).

Interaction Plots for Combined Effects from Two Factors

For Resolution III DOE investigations, there is a specific need to investigate the *visually apparent* interactions (when the level of one factor seems to influence the effect of the second factor) hinted by the two effect lines having different slopes (and sometimes crossing each other). From a visual assessment of the relative slopes values and line crossing.

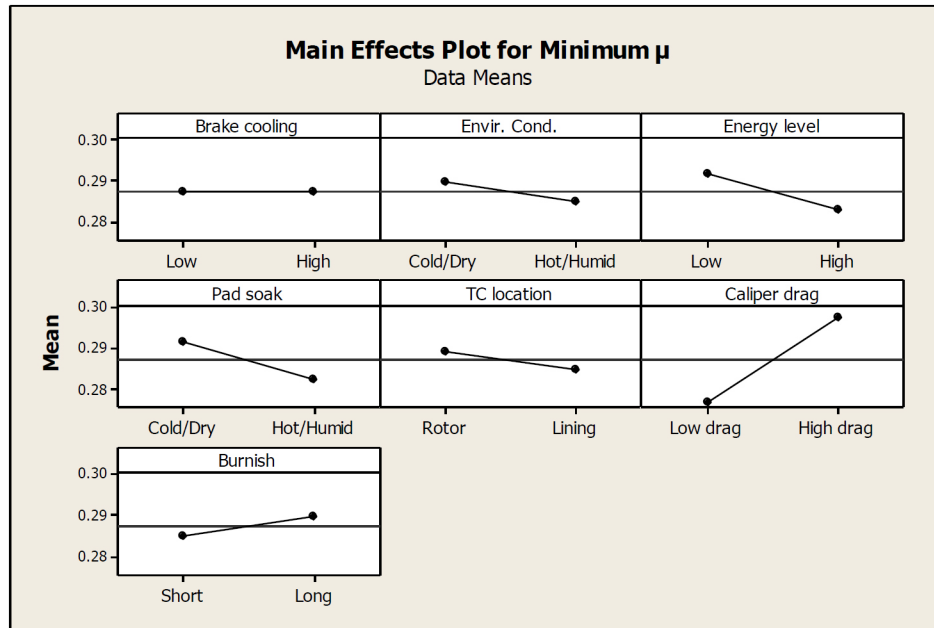


Figure 8. Main effects on minimum friction coefficient (μ) as a function of each of the seven factors

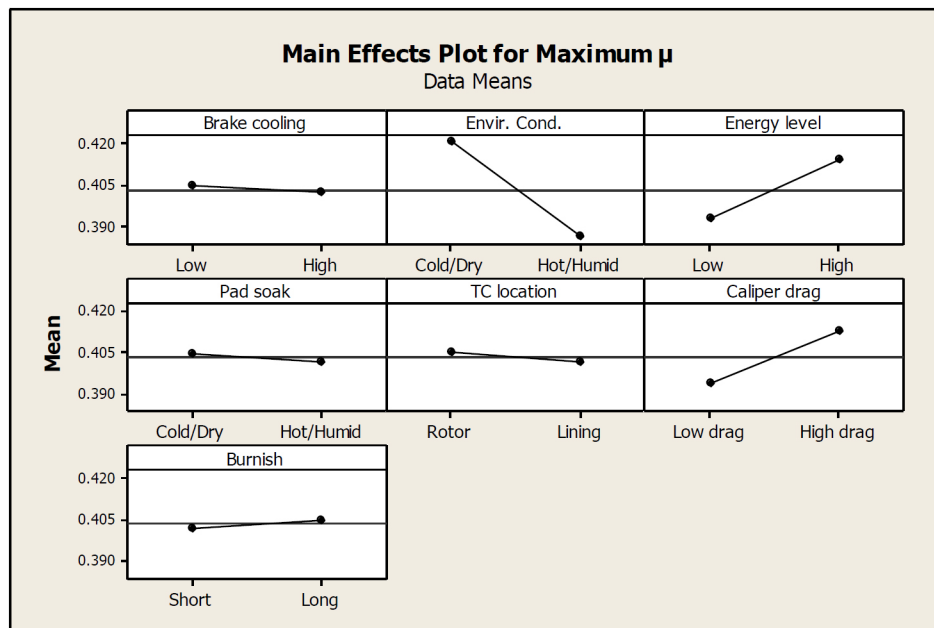


Figure 9. Main effects on maximum friction coefficient (μ) as a function of each of the seven factors

Figure 10 suggests the combinations of the following factors may generate significant interactions: *brake cooling / burnish*; *environmental conditions / energy level*; *energy level / caliper drag*; *pad soak / thermocouple location*; and *thermocouple location / burnish*.

In order to provide a statistical evaluation (instead of a visual subjective assessment) we conducted a two-way normal analysis of means for the specific metric with the two factors

seemingly interacting. On this type of analysis, the reference line (plotted at zero) and the lower and upper decision limits represent the hypothesis that the effect is equal to zero (that no interaction exists). When one of more effects is beyond the decision limits, then you can conclude that there is statistical evidence of the interaction. From this analysis, only the *energy level / caliper drag* and *environmental conditions / energy level* combinations are to be statistically significant as shown in Figs. 11 and 12.