



SURFACE VEHICLE RECOMMENDED PRACTICE

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Inertia Dynamometer Brake Squeal Noise Test Procedure for Vehicles with Regenerative Systems

RATIONALE

Foundation brakes used on hybrid and electric vehicles (EVs) with regenerative (regen) braking tend to have lower average operating temperatures than vehicles using internal combustion engines. Besides, the intervention of the foundation brakes during vehicle deceleration is a function of the blending technology and the capabilities of the propulsion system. Some vehicles can achieve a high percentile of decelerations during regular vehicle use using only the regenerative system with minimal foundation brake intervention. Lastly, there is a lack of engine noise, a high percentage of hybrid and electric vehicles operating in cold weather, and some electric vehicles with high-performance capabilities that demand a new approach to measure and characterize brake squeals. This document addresses multiple aspects of brake squeal for regenerative braking systems by (a) focusing on lower operating brake temperatures also induced by more extended periods between wheel brake events, (b) reducing the brake pressures for several modules (including burnish), and (c) defining test sequences and brake profiles applicable to regenerative braking systems.

FOREWORD

This document adapts the main modules and braking modes from SAE J2521 for speed, brake pressure, and temperature regimes typical of vehicles with regenerative braking systems. This document includes the new test modules that incorporate profiles to reflect different levels of brake blending (combining decelerating torques from the foundation brakes and the electric machine), which could be critical to squeal noise. A significant change addressed by this document is the adoption of brake torque deceleration profiles to recreate the regenerative brake in EVs. Following the approach of using braking profiles, germane to SAE J2521, the simplified regenerative brake profiles reduce the complexity of implementing the test sequence. The test starts with optional modules for high-speed snubs, low-speed stops, and snubs with regenerative braking profiles.

The test matrix (applicable to disc and drum) includes five schedules. All modules include a matrix of high-speed snubs and low-speed stops and snubs with regenerative braking profiles:

- Schedule A—Standard: Standard test sections with deceleration, drag, and backward/forward braking at various temperatures, pressures, and speeds.
- Schedule B—Optional: Noise during cold modules to assess noise propensity below 50 °C and at or below 0 °C.
- Schedule C—Optional: Noise during modules at mild temperature and high humidity.
- Schedule D—Optional: Noise after a fade to assess the influence of high-temperature excursions.
- Schedule E—Optional: Noise during several backward/forward cold modules to assess noise propensity below 25 °C, cooling air at or below 5 °C with high air humidity.

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This document establishes the minimum standard specifications regarding test setup, inertia-dynamometer characteristics, test sequence, and test report items. Deviations from or changes to this procedure to accommodate a specific project are feasible if discussed and agreed upon among the interested parties before the actual staging of the test(s).

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1. SCOPE

The SAE J3211 procedure applies to squeal evaluation for foundation brakes using single-ended inertia dynamometers for friction couples used on vehicles with regenerative braking systems. This document applies to squeal noise occurrences for on-road passenger cars and light trucks with a gross vehicle weight rating of 4536 kg or below and with at least one rechargeable energy storage system as a source for propulsion. The procedure incorporates aspects related to (a) minimum inertia dynamometer capabilities, (b) fixture requirements and setup, and (c) test sequences with emphasis on brake temperatures, brake pressure profiles, and strategies to represent brake blending.

For this document, squeal occurs when the peak noise level is at least 70 dB(A) between 1.25 and 16 kHz for tests using full suspension corners or complete axle assemblies, or between 2 and 16 kHz for brakes not using an entire suspension corner.

Test facilities intending to use this document, building on their expertise in conducting SAE J2521, shall review in detail the changes to test parameters (mainly brake temperatures and brake pressures) for legacy modules.

This document also applies to vehicles with electromechanical braking systems to actuate the foundation brake. The test requester and the test facility are responsible for converting the hydraulic pressure levels into their equivalent clamping forces for brakes using electromechanical actuation.

Before using this document for chassis dynamometer testing, review in detail the specifics related to at least (a) instrumentation, including in-cabin microphones; (b) threshold levels for noise detection; (c) temperature control priority between the front and rear axles; (d) vehicle loading and load distribution; (e) cooling air and environmental conditioning; (f) detailed terminology and labeling of channels and sensors; and (g) the regenerative settings and the state of charge during the test.

Before using this document along with other methods to recreate the regenerative brake blending (e.g., Software-in-the-Loop or Hardware-in-the-Loop), consider (a) the vehicle powertrain, blending architecture and its applicable models, (b) actual profiles intended to recreate (e.g., control strategies, state of charge, test scenarios), and (c) actual embodiment of the simulation and integration with the native controls of the brake dynamometer.

This document does not include noise from other sources (e.g., parking brakes, electric machines, driveline components).

1.1 Purpose

This document establishes a standard method that identifies a brake assembly's propensity to generate squeal noise under various test conditions for vehicles with regenerative braking. The result is an evaluation of brake noise under defined braking conditions considered most relevant to automobile braking system development.

The test matrix describes the test conditions and steps to investigate the influence of pressure, temperature, and velocity on squeal noise behavior. Each module within the test matrix intends to replicate vehicle conditions to compare different brake corner components.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

SAE J2468	High-Preload Deflection and Compressibility Test Procedures for Friction Materials
SAE J2521	Inertia Dynamometer Brake Squeal Noise Test Procedure for Vehicles without Regenerative Systems
SAE J2598	Automotive Disc Brake Pad Natural Frequency and Damping Test
SAE J2789	Inertia Calculation for Single-Ended Inertia-Dynamometer Testing
SAE J2933	Verification of Brake Rotor Modal Frequencies
SAE J2986	Brake Pads, Lining, Disc, and Drum Wear Measurements
SAE J3079-2	Low-preload Deflection Measurement for Brake Pads, Noise Shims, and Brake Pad Assemblies
SAE J3152	Taxonomy and Guidelines for Design, Fabrication, and Installation of Brake NVH Fixtures for Inertia Dynamometer Testing

2.1.2 IEC Publications

Available from IEC Secretariat, 3 rue de Varembe, PO Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 0211, www.iec.ch.

IEC 60942	Electroacoustics - Sound calibrators
IEC 61672-1	Electroacoustics - Sound Level Meters - Part 1: Specifications

2.1.3 ISO Publications

Copies of these documents are available online at www.iso.org/store.

ISO 3966	Measurement of fluid flow in closed conduits - Velocity area method using Pitot static tubes
ISO 6310	Road vehicles - Brake linings - Compressive strain test methods

2.1.4 VDA Publications

Available from German Association of the Automotive Industry (Verband der Automobilindustrie e.V. [VDA]), Behrenstraße 35, 10117 Berlin, Germany, Tel: +49 30 897842 - 0, <https://webshop.vda.de/VDA/en/>.

VDA 300	Development Guideline on Quality Control of Disc Brake Linings
VDA 303	Description of Noisy Brake Applications Concerning Brake Squeal
VDA 305	(EKB 3008) Data Exchange Format Description
VDA 306	Definition of Charts for the Evaluation of Brake Noise Data/Dynamometer
VDA 307	(EKB 3010) Brake Noise Dyno Test Certification

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

SAE J2625	Automotive Vehicle Brake Squeal Test Recommended Practice
SAE J2786	Automotive Brake Noise and Vibration Standard Nomenclature
SAE J3001	Brake Insulator Damping Measurement Procedure

2.2.2 IEC Publications

Available from IEC Secretariat, 3 rue de Varembe, PO Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 0211, www.iec.ch.

IEC 61672-2	Electroacoustics - Sound Level Meters - Part 2: Pattern Evaluation Tests
IEC 61672-3	Electroacoustics - Sound Level Meters - Part 3: Periodic Tests

3. DEFINITIONS

The following definitions apply to facilitate the application of this SAE document.

3.1 APPARENT FRICTION FOR DISC BRAKES

Per Equation 1:

$$\mu = \frac{1 \times 10^6 \cdot T}{2 \cdot (p - p_{Threshold}) \cdot A_p \cdot r_{eff} \cdot \eta} \quad (\text{Eq. 1})$$

where:

μ = apparent friction for disc brakes (unitless)

3.2 DRUM BRAKE EFFECTIVENESS (C^*)

Per Equation 2:

$$C^* = \frac{1 \times 10^6 \cdot T}{(p - p_{threshold}) \cdot A_p \cdot r_{eff} \cdot \eta} \quad (\text{Eq. 2})$$

where:

C^* = effectiveness for drum brakes (unitless)

T = output torque (N·m)

p = brake pressure (kPa)

$p_{threshold}$ = minimum pressure required to start developing braking torque; unless otherwise indicated by the test requester or measured as part of the project, use a zero value (bar)

A_p = total piston area acting on one side of the caliper for disc brakes; total wheel cylinder area for drum brakes (mm²)

r_{eff} = radial distance from the centerline of the piston to the axis of rotation for disc brakes; internal drum diameter divided by two for drum brakes unless the requester provides other dimensions (mm)

η = brake efficiency; unless otherwise indicated by the test requester or measured as part of the project, use a value of one (100%)

3.2.1 For dynamic brake applications, calculate the average-by-distance friction coefficient or effectiveness value between t_1 and t_2 per 8.1.

3.2.2 For brake drag applications, calculate the average-by-time friction coefficient or effectiveness value between t_1 and t_3 per 8.2.

3.3 GROSS VEHICLE WEIGHT (GVWR)

Maximum vehicle weight indicated by the manufacturer.

3.4 BRAKING SPEED

Linear speed at the onset of brake pressure when the speed reduces during the brake application.

3.5 DRAG SPEED

Linear speed at the onset of brake pressure when the speed remains constant during the brake application.

3.6 INITIAL BRAKE TEMPERATURE (IBT)

Rotor or drum temperature at the start of the brake application.

3.7 TIRE DYNAMIC ROLLING RADIUS

Equivalent tire radius generating the revolutions per mile (rpm) published by the tire manufacturer for the specific tire size per Equation 3. Use the dynamic tire rolling radius to calculate the dynamometer rotational speed for a given linear vehicle speed/mm.

$$RR = (1\,609\,344)/(2 \cdot \pi \cdot rpm) \quad (\text{Eq. 3})$$

where:

RR = tire dynamic rolling radius (mm)

rpm = tire manufacturer specification for revolutions per mile indicated by the tire manufacturer

4. TEST EQUIPMENT

4.1 Single-ended brake inertia dynamometer that can perform dynamic brake applications with deceleration- and pressure-controlled brake applications. The test system must conduct (a) brake drags at constant pressure, (b) brake drag with brake pressure profiles, and (c) regenerative braking decelerations when the main motor and drive recreate the torque of the electric machine from the vehicle.

4.2 Reversible motor and drive control to conduct the brake drag applications at no less than 90% of the nominal brake drag speed.

NOTE: Calculate motor torque based on the highest of the three following values: (a) brake drag at base speed and 32.5 bar brake pressure, (b) acceleration rate during brake fade modules, and (c) motor torque used for inertia simulation during dynamic brake applications, including regen profiles.

4.3 Control system that can perform brake applications at constant pressure, pressure profiles, regenerative brake profiles, and constant deceleration (torque control).

4.3.1 Pressure ramp rate of at least 100 bar/s (see 8.1) and a maximum pressure of at least 160 bar.

4.3.2 Overshoot of less than 1 bar during dynamic brake applications.

4.3.3 Average pressure control within 0.25 bar of the target value (set point) during pressure profiles.

4.3.4 Deceleration control and overshoot within 0.5 m/s² of the target value (set point).

4.3.5 (Optional) Control system and associated hardware for foundation brakes with electromechanical actuation.

4.4 Cooling air system directed at the brake.

- 4.4.1 Control the air speed so it does not blow away wear debris or create noise above the background limit of 64 dB(A) above 900 Hz. The cooling air remains on during the brake events.

NOTE 1: The 64 dB(A) limit provides 6 dB(A) separation, which is a 2:1 separation or half the threshold limit to detect noisy brake events above 70 dB(A).

NOTE 2: Other threshold levels, like brake noise evaluation for electric vehicles, could be more appropriate. In such cases, confirm with the test requester and the testing facility.

- 4.4.2 Set up the duct outlet 300 to 400 mm away from the rotor outside diameter with an air duct with a hydraulic diameter of 200 to 300 mm. Adjust cooling air to 10 m/s (35 km/h) measured at the duct outlet; adjust the background noise level from 4.4.1 if needed.

NOTE 1: If the above conditions cannot be achieved, agree with the test requester and document it on the final test report.

NOTE 2: Alternatively, use a cooling airflow from 1000 to 2000 m³/h, ensuring a background noise level per 4.4.1.

NOTE 3: Since the cooling air setup is a critical subsystem of the inertia dynamometer, which affects test variability and duration, establish proper definitions and test conditions for the test project. Measure airflow, assess cooling rates at specific temperatures and test speeds, and review cycle times and overall temperature regimes during the tests to better understand the conditions and effects on noise and friction behavior.

4.4.3 Climatic Controls and Soak Conditions

- 4.4.3.1 Table 1 summarizes the conditions for the different soaks during the test schedules. Figure 1 shows two typical cooling air setups for disc brake assemblies.

- 4.4.3.2 Document in the test reports the actual cooling air orientation relative to the brake and the brake rotation.

NOTE 1: Allow short excursions beyond the control limits for temperature and humidity when the climatic control unit switches coils to implement the thermodynamic transitions.

NOTE 2: Monitor the climatic control unit's condition and performance for coil or damper freeze when transitioning to temperatures below 5 °C. Hot and high-humidity conditions in the laboratory area can exacerbate this behavior.

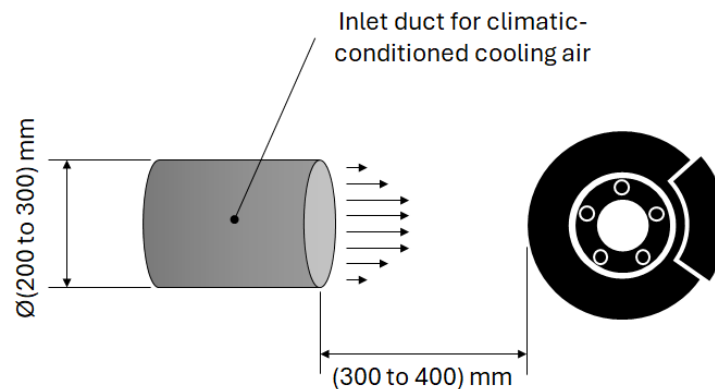
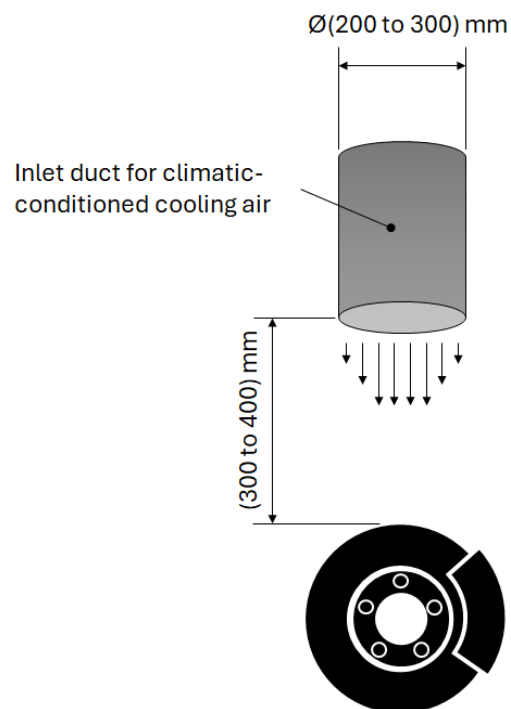
NOTE 3: During cold modules below the dew point of the environmental control system, control only the cooling air temperature.

- 4.4.3.3 In agreement with the test requester and the testing facility, keep the cooling air setup the same and use the same fixture orientation (left- or right-hand) to maintain the brake assembly's same cooling behavior (including noise insulators or shims) for the same project.

Table 1 - Climatic controls and soak conditions

Schedule	Soak Number	Air Temperature °C	Relative Humidity %RH	Soak Period Minutes	Maximum Time to Reach Conditions Minutes	Brake Speed During Soak Period km/h
A	1	20 ± 2	50 ± 10	20 ± 2	50	5
A	2	10 ± 2	30 ± 10	20 ± 2	50	5
A	3	-5 ± 3	30 ± 15	20 ± 2	60	5
B	4	-20 ± 3	n.a.	60 ± 2	90	0
B	5	-25 ± 3	n.a.	20 ± 2	40	0
C	6	20 ± 2	80 ± 15	60 ± 2	60	5
D	7	20 ± 2	50 ± 10	20 ± 2	50	5
E	8	0 ± 3	80 ± 15	60 ± 2	90	0
E	9	5 ± 3	>75	60 ± 2	60	0
E	10	-5 ± 3	80 ± 15	60 ± 2	60	0

Note: n.a. = not applicable.

**Figure 1A - Horizontal layout****Figure 1B - Vertical layout****Figure 1 - Recommended setup for cooling air**

4.5 Automatic data collection system capable of recording the following channels at 50 Hz minimum:

4.5.1 Brake equivalent linear speed (km/h)

4.5.2 Brake input pressure (kPa)

4.5.3 Brake output torque (N·m)

4.5.4 Brake apparent friction or effectiveness per 3.1 and 3.2

4.5.5 (Optional) Brake fluid displacement (mm³)

4.6 Automatic data collection system capable of recording the following channels at 10 Hz minimum:

4.6.1 Brake rotor or drum temperature (°C)

4.6.2 (Optional) Brake pad or brake shoe temperature (°C)

4.6.3 Cooling air temperature, relative humidity (or absolute humidity), and speed (or airflow)

5. TEST FIXTURE

5.1 The test fixture significantly influences the test complexity and logistics associated with the test preparation and setup. It ultimately can affect the dominant frequencies and sound pressure levels observed during the test. The fixture level specified for a given project results from many decisions and shall remain the same for the same project or noise investigation. The same approach applies to the preloading method to impose suspension forces during testing.

5.2 Refer to SAE J3152 for a detailed description of the different styles, preloading methods, design, manufacturing, assembly, and installation guidelines.

5.3 Review in detail with the test facility and document the project's loading strategy and settings when using an external loading system on the fixture. The loading can be fixed for the entire duration, changing from section to section, or dynamic loading changing in real time during the test sequence.

5.4 Specify for the project the method required to drive the brake corner (direct connection to the dynamometer shaft, spool-driver in combination with a constant velocity driveshaft, wheel center driver with a constant velocity driveshaft, or driving through the wheel/tire assembly) and the details regarding the driver material and design. See Figure 2.

NOTE 1: The drive system and connection to the main dynamometer can significantly influence a given brake's noise propensity and the dominant frequencies during the test. Document and use the same design and material for the project as a best practice to reduce test-to-test and dyno-to-dyno variability.

NOTE 2: When feasible or indicated by the test requester, the spool-driver design should mimic a reference wheel design's interface and force distribution.

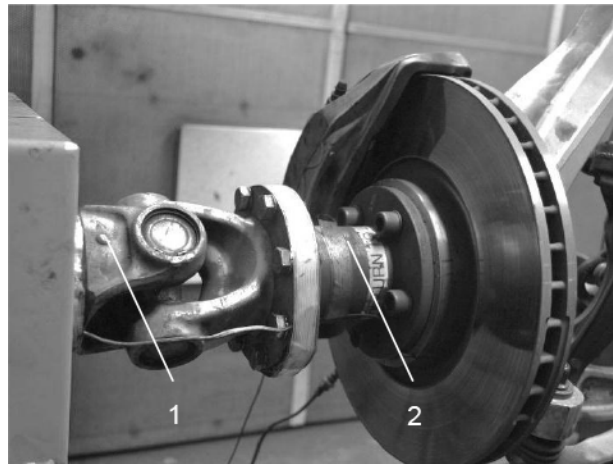


Figure 2A - Spool driver

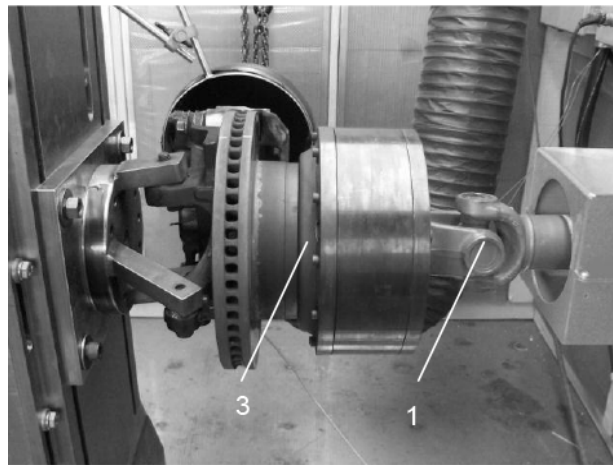


Figure 2B - Wheel center driver

Key:
1 – Constant velocity driveshaft
2 – Spool driver
3 – Wheel center driver

Figure 2 - Brake driving system

5.5 Report the brake fixture level and the drive method used for a test project. Refer to VDA 307 (EKB 3010).

6. TEST INERTIA

Unless otherwise indicated by the test requester, determine the test inertia per the default or the torque index methods in SAE J2789 with the vehicle loaded at GVWR for decelerations below 0.65 g.

7. PARTS PREPARATION AND TEST SETUP

7.1 Temperature Measurement

7.1.1 Unless otherwise specified by the test requester, use a new rotor and brake pads or new drum and brake shoe linings for each test.

7.1.2 For brake discs, install a thermocouple at a depth of 1.0 mm on the outboard face at the braking surface's centerline.

NOTE: As an alternative method for measuring rotor temperature and in agreement with the test requester, use an infrared measurement on the outside diameter of the inboard face of the disc. When using infrared measurements, the outside diameter of the rotor coating with a heat-resistant black nonreflective paint provides an emissivity consistent with that required by the infrared measurement system. Obtain the correct emissivity settings from the test requester or use an agreed-upon method. Unless it is readily available for the rotor design, this method performs a trial test to establish the infrared reading correlation with the embedded thermocouple. At appropriate intervals during testing, ensure dust or debris does not accumulate on the lens.

7.1.3 (Optional) For brake pads, install one thermocouple at a depth of 2.0 mm near the center of each pad's friction surface. For disc brake pads with grooves, install the thermocouple at least 4.0 mm from the groove edge on the leading side of the pad. Install the thermocouple between 3 mm and 4 mm on the leading side of the piston outside diameter near the friction surface center for inboard pads on single-piston calipers.

7.1.4 When conducting schedule C (including the fade section), confirm with the test requester the need and location for an additional thermocouple on the backing plate or noise shim to monitor the temperature.

7.1.5 Install a thermocouple at a depth of 1.0 mm for brake drums on the braking surface's centerline.

7.1.6 (Optional) Install a thermocouple at a depth of 1.0 mm near the center of the most heavily loaded shoe's friction surface for brake shoes.

7.1.7 Use the same temperature measurement and location for the same project.

7.1.8 Document and report on the final test report when using a different control thermocouple for the test.

7.1.9 The installation of redundant temperature measurements can prevent accidental overheating due to thermocouples or wiring failures.

7.2 Microphone Location

Position the microphone in the vertical plane and perpendicular to the brake axis, pointing downward. Locate the center of the microphone:

- a. 100 mm outboard from the wheel hub mounting surface along the axle's centerline
- b. 500 mm above the brake rotating axis
- c. On the vertical plane of the rotor or drum axis (see Figure 3)

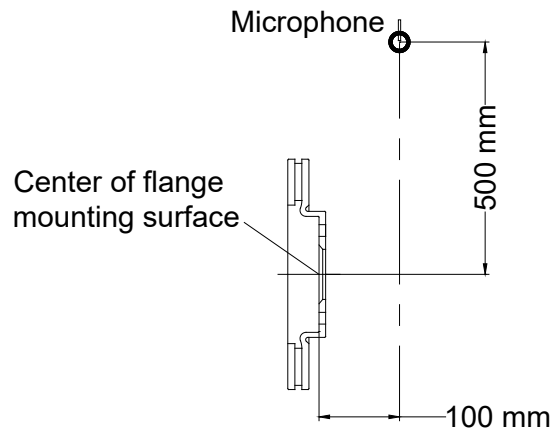


Figure 3 - Microphone orientation and position relative to flange center

7.3 Noise Measurements Settings

- 7.3.1 Unless the test requester specifies, use a microphone conforming to IEC 61672-1 Class 2 or better with a corresponding windscreen.
- 7.3.2 Before and after the test, use a calibrator of the same microphone class at 1 kHz per IEC 60942.
- 7.3.3 Use a frequency analyzer or digital data acquisition system to record the sound spectrum in the time domain. The system must compute and record narrowband sound pressure spectra using the following parameters and capabilities:
- 7.3.3.1 500 to 20000 Hz frequency bandwidth, with a frequency resolution of 25 Hz.
 - 7.3.3.2 Use peak-hold averaging with 66.7% overlap processing.
 - 7.3.3.3 Apply the Hanning windowing method to the time-based records.
 - 7.3.3.4 Anti-aliasing filtering.
 - 7.3.3.5 A-type signal weighting.
- NOTE: Due to the A-weighting method's complexity, ensure the noise analyzer has the proper configuration before testing. Any plausible post-test correction algorithm is beyond the scope of this SAE document.
- 7.3.4 Measure the sound pressure level (SPL) in dB(A) for all brake applications for all sections.
- 7.3.5 Ensure the background noise level inside the test chamber with the cooling air system operating does not have peaks above 64 dB(A) above 900 Hz.
- 7.3.6 Noise measurement duration (recording) is the same as the brake application duration for all sections:
- 7.3.6.1 From t_0 to t_4 for dynamic brake applications; see 8.1.
 - 7.3.6.2 From t_1 to t_3 for brake drag applications; see 8.2.
- 7.3.7 Save microphone information as peak hold spectra, time recordings, peak-hold history at fixed intervals, peak dB(A), and the corresponding frequency at a fixed interval.
- 7.3.8 (Optional) Use accelerometers to validate noisy brake events. Before commencing testing, define the quantity, location, and data validation technique with the test requester.

- 7.4 For disc brakes, the assembled lateral run-out shall not exceed 50 μm when measured on the outboard surface and 10 mm from the outside diameter.
- 7.5 Set the diametric cage clearance to the value indicated by the test requester, the vehicle service manual, or the brake assembly print for drum brakes. If no other information is available, set the diametric cage clearance to 0.6 to 0.8 mm, measured at the shoes' center. Rotate to check for excessive drag and adjust if necessary.
- 7.6 (Optional) When requested, measure wear on the components of the friction couple using SAE J2986.

8. TEST CYCLES

8.1 Dynamic Brake Application Using Constant Pressure or Constant Torque

- a. During brake events where the brake speed reduces as a function of the brake torque under constant pressure, the pressure level is constant after reaching the set point. Brake events during brake stops or snubs (burnish, intermediate conditioning, and deceleration modules) utilize constant pressure control. Apply a pressure ramp rate to provide a rise time to the nominal pressure of 0.5 second.
- b. During brake events where the brake speed is reduced as a function of constant brake torque, the control system modulates the pressure level to maintain the target brake deceleration for the brake under testing. Brake events during the fade stop module utilize constant deceleration control. To achieve the target deceleration level during dynamic braking cycles, use a pressure ramp rate of 150 bar/s $\pm$ 50 bar/s.

Figure 4 illustrates the main time stamps characterizing the brake dynamic brake application.

8.1.1 Time t_0

Brake application initiation. At this time, the pressure starts to rise.

8.1.2 Time t_1

Time at which pressure or torque reached the target level. At this time, the brake reaches its target level for torque or pressure control. At time t_1 , calculating the average by time and the average by distance begins.

8.1.3 Time t_2

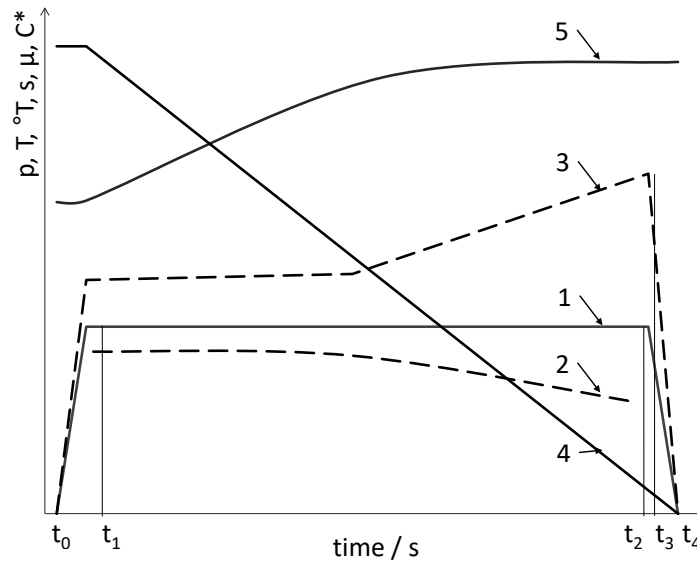
Time at the end of the averages. At time t_2 , the inertia-dynamometer data acquisition system terminates the average calculation by time and average by distance. Time t_2 is the end of the stable portion of the brake application, and t_2 is when the speed is 0.5 km/h above the release speed (t_3).

8.1.4 Time t_3

Time at release speed. At time t_3 , the inertia-dynamometer servo controller releases the brake (specified in 8.1.3).

8.1.5 Time t_4

Time at brake pressure and torque lost. At time t_4 , pressure and torque are below the minimum thresholds. The inertia-dynamometer considers the braking event complete.



Key:
 1 – Brake pressure (p)
 2 – Brake coefficient of friction or drum brake effectiveness (μ , C^*)
 3 – Brake torque output (T)
 4 – Brake speed (s)
 5 – Brake temperature ($^{\circ}T$)

Figure 4 - Time stamps for typical brake deceleration (example at constant brake pressure)

8.2 Brake Drag Applications Using Brake Pressure Profiles

Figure 5 illustrates the main time stamps used to characterize the brake drag application at constant brake speed with changing pressure during the braking event. The low-speed and backward/forward modules utilize brake pressure profiles.

8.2.1 Time t_0

Brake application initiation. At this time, the pressure starts to rise. The ramp rate from t_0 to t_1 provides a rise time to the nominal pressure minus 2.5 bar of 0.5 second.

NOTE: 1 bar = 100 kPa = 0.1 MPa = 14.5 psi

8.2.2 Time t_1

The start time of the 1 bar/s pressure profile equals 0.5 second. At time t_1 , brake pressure equals the nominal pressure p minus 2.5 bar, and the calculation of average-by-time effectiveness begins. For the zero-bar pressure profile, t_1 equals 2.5 seconds.

8.2.3 Time t_2

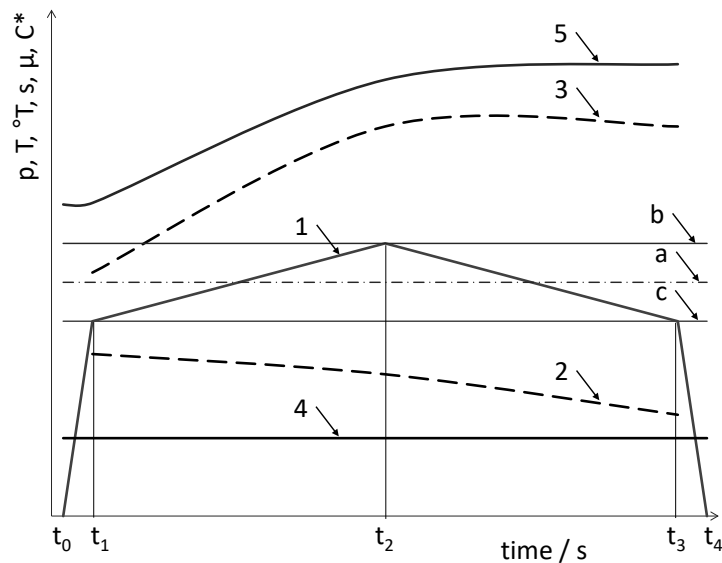
Time in the middle of the 1 bar/s profile equals 5.5 seconds. At time t_2 , brake pressure equals the nominal pressure " p " plus 2.5 bar. For the zero-bar pressure profile, t_2 equals 5 seconds.

8.2.4 Time t_3

Time at the end of the 1 bar/s pressure profile equals 10.5 seconds. At time t_3 , the brake pressure equals the nominal p minus 2.5 bar. At time t_3 , the calculation of average-by-time effectiveness finishes. For the zero-bar pressure profile, t_3 equals 7.5 seconds.

8.2.5 Time t_4

Time at brake pressure and torque lost, equal to 11 seconds. At time t_4 , pressure and torque are below the minimum thresholds. The inertia-dynamometer considers the braking event complete. For the zero-bar pressure profile, t_4 equals 10 seconds. The ramp rate from t_3 to t_4 provides a pressure release time from the nominal pressure minus 2.5 bar to zero of 0.5 second.



Key:

- 1 – Brake pressure (p)
- 2 – Brake coefficient of friction or drum brake effectiveness (μ , C^*)
- 3 – Brake torque output (T)
- 4 – Brake speed (s)
- 5 – Brake temperature ($^{\circ}T$)
- a – Nominal brake pressure for the profile
- b – Nominal brake pressure plus 2.5 bar
- c – Nominal brake pressure minus 2.5 bar

Figure 5 - Typical brake drag application (pressure profile) with time stamps

Figure 6 illustrates the pressure profiles during brake drag application. The control system and the inertia dynamometer's servo controller shall follow the pressure trace.