

Vehicle Integration Factors Affecting Brake Caliper Drag

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ABSTRACT

Disc brakes operate with very close proximity of the brake pads and the brake rotor, with as little as a tenth of a millimeter of movement of the pads required to bring them into full contact with the rotor to generate braking torque. It is usual for a disc brake to operate with some amount of residual drag in the fully released state, signifying constant contact between the pads and the rotor. With this contact, every miniscule movement of the rotor pushes against the brake pads and changes the forces between them. Sustained loads on the brake corner, and maneuvers such as cornering, can both produce rotor movement relative to the caliper, which can push it steadily against one or both of the brake pads. This can greatly increase the residual force in the caliper, and increase drag. This dependence of drag behavior on the movement of the brake rotor creates some vehicle-dependent behavior. Major factors affecting rotor movement include wheel bearing stiffness, wheel radius, vehicle mass and mass distribution, and brake corner geometry. The present work studies two vehicle-integration dependent mechanisms which can affect brake drag. The first involves rotor movement due to sustained tire/wheel loading conditions and brake corner geometry, and is examined through a case study involving two vehicles. The second involves rotor movement due to cornering loads. In both cases, rotor movement is related to brake drag by component dynamometer measurements of brake drag versus small axial movements of the rotor.

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INTRODUCTION

At first glance, the brake corner during normal operation appears to be a rigid structure, devoid of any behavior in the off-brake condition that could be construed as interesting. It supports the weight and dynamics loads of the vehicle while allowing the wheel to rotate and transmit power, and does so with remarkably little complaint. In most brake performance calculations, the assumption of perfect rigidity may reasonably hold true. However, for certain performance considerations - most notably, residual caliper drag - the many tiny movements of components relative to one another within the brake corner can be of significance. At this level of motion - measured in terms of microns up to perhaps a couple millimeters in extreme conditions - the brake corner is alive with activity. Measuring the residual caliper to pad force dynamically in-vehicle shows that characteristics such as rotor lateral runout and rotor movement during cornering show up just as clearly in the residual force signal as it would in a direct geometric measurement [1].

Direct real-time measurement of residual drag on a caliper installed in a vehicle is a fundamentally difficult task, especially to do so without affecting the results. This is due to the fact that brake corner components are engineered to

support extremely high loads without fatigue failures and with little deflection, and therefore operate with very little strain. This makes the use of strain-based measurements (common force and torque measurement technology) difficult. If parts are modified to increase the strain, then their behavior may no longer be representative of the actual case. A common on-vehicle measurement technique is to use a chassis dynamometer, and compare overall non-aero road load with and without brakes installed [3,6]. This is done after carefully warming up all of the components to achieve as close to steady losses as possible. This allows for a measurement of brake drag (with some limitations on resolution; around 1.0 Nm/axle is typical) with the brake corner fully loaded. Barring specific vehicle-level measurements of brake drag, the effects of brake drag will still show up in coast down tests to determine road load losses, which may then lead to root-causing efforts with any component in the loss stream (including the brakes).

It is common for brake engineers to use a more sensitive, component or brake corner subsystem level dynamometer measurement to engineer caliper drag behavior for their designs. Here, an improvement in measurement resolution is usually achieved, but the effect of loads and resultant rotor movement relative to the caliper is mostly removed (some

relative movement still occurs during braking and release, due to deflection of components under braking loads, and movement due to rotor lateral runout of course remains). Some recent publications cover these measurements in some detail [2,3].

The present paper explores two vehicle-integration related influences on brake drag, using a combination of sensitive dynamometer measurements of drag, in-vehicle measurements of brake rotor movement, and simple free-body diagram based computations of rotor deflection. One of these influences involves the brake rotor shifting position as the vehicle starts and stops. The other involves the deflection of the rotor during cornering and the significance of the resultant increase in drag to the overall 'real world' losses of energy to the brake system.

The present paper is organized into four major sections:

1. Vehicle Integration Influence on Drag
2. Component Dynamometer-based measurement of drag vs., rotor movement
3. Case study of two vehicles and measurement of rotor movement
4. Additional Consideration - Drag due to Cornering

1. VEHICLE INTEGRATION INFLUENCE ON DRAG

The modern disc brake caliper contains numerous friction interfaces, and has sliding components (such as pistons and guide pins) capable of retaining residual force and transmitting it to the pad/rotor interface even when fully released. As such, there are a number of mechanisms by which residual drag can occur, such as residual force from the piston seal, or excessive slide force in the housing or pad guiding systems. However, these mechanisms are largely internal to the brake corner and are not directly affected by installation of the brake corner into a vehicle. The key parameter that changes when transitioning from corner subsystem to a full vehicle is that the brake corner bears the load of the vehicle, and connects the vehicle mass with the tires and the road. The mechanism by which these loads can affect caliper drag is by influencing the position of the brake rotor relative to the caliper, in turn by causing deflection of the wheel bearing (and to a lesser extent the suspension knuckle).

It is especially problematic for brake drag when the rotor is in one position as the brakes are applied and released, and then shifts to a different position after the caliper has been released (after the off-brake position and 'running clearance' of the caliper has been set to the original rotor position) Movement of the brake rotor relative to the caliper may cause the rotor to push up against the brake pads. The movement will initially attempt to slide the pad it first makes contact with. As rotor movement continues, it will slide the pad into the caliper (either piston or fingers), and then start pushing

the housing (of a sliding caliper) over against the other pad. Eventually, at high enough rotor displacements, the rotor movement will translate the caliper (with both pads) along its sliding mechanism completely. In the case of a fixed caliper, rotor movement will first slide the pad it contacts, and will then push the pad back against the piston(s) and piston seal(s), which will ramp up residual forces in the caliper, and therefore caliper drag, precipitously.

Intuitively, one might suppose that movement of the rotor will have a tendency to 'push back' or 'knock back' the brake pads away from itself, thereby relieving brake drag. While this is true in extreme conditions (such as the inertial load and rotor movement caused by extremely rough road operation, or high lateral acceleration cornering events), in many 'everyday' driving conditions the slide resistance forces in the pads and housing will behave elastically. The elastic behavior of residual forces in the caliper has been documented by in-vehicle measurements [1], and are further covered in the next section.

The Elasticity of Pad Slide Forces

When the brake rotor pushes against a brake pad, it does not slide right away; in fact, it will resist sliding in a highly elastic manner for a short distance (generally on the order of 0.1 to 0.5mm) until it slides. This elasticity shows up in the linear rise of pad force versus displacement in a typical slide force test (see the example below in [figure 1](#)). At first glance, it is not immediately evident why this elastic behavior takes place, but it is actually due to a combination of pad taper and the pad abutment spring clips.

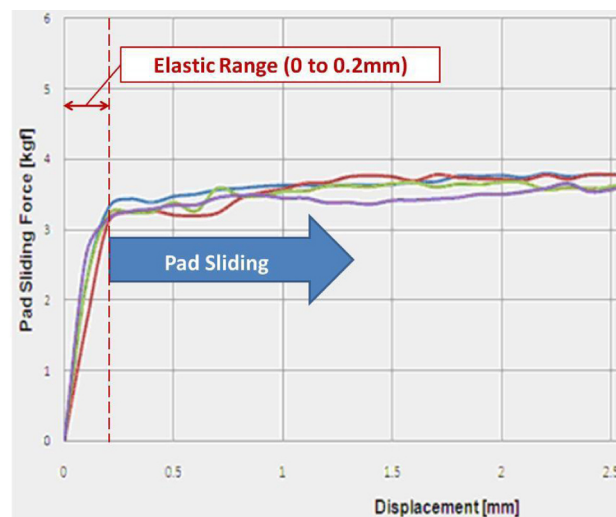


Figure 1. Typical Brake Pad Slide Force Measurement (3 repetitions)

It is quite rare that a brake pad and its guiding mechanism - even a completely new pad in a new caliper - will be perfectly aligned with the brake rotor. There will generally be some lack of parallelism between the pad face and the rotor face, and some lack of orthogonality between the pad guiding mechanism and the disc face. These imperfections are due to

manufacturing variation in the caliper bracket the brake pads, and in the spring clips. When the pad wears with normal use, it will also develop taper wear. Figure 2 below shows how as the brake disc pushes up against a taper-worn pad, it causes a moment on the pad that will twist it against the elastic restraint of the spring clips, which will cause elastic slide force behavior. In addition to this, the pad spring clip itself may allow a small amount of elastic deflection in the axial (pad apply and release) direction, which will add to this elasticity.

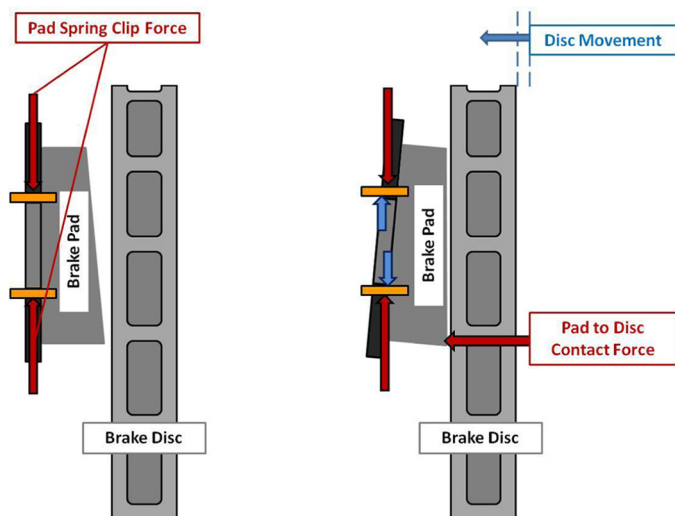


Figure 2. Elasticity of Pad Slide Forces due to Taper Wear

It is worth noting as well that on the small scale of movement under consideration (tenths of a mm), the housing guide mechanism of a sliding caliper will have some elasticity in its slide behavior due to the presence of rubber bushings in the system (typically placed at the tip of one of the guide pins, at the base of the pins in the case of internally fitted guide pin boots, or along the length of the guide pins in the case of the full rubber bushed pins commonly used in reverse-pin sliding calipers).

2. COMPONENT DYNAMOMETER MEASUREMENTS

A dedicated off-brake caliper drag dynamometer was used to measure how caliper drag was affected by rotor movement within the caliper. The particular dynamometer used had two symmetric ends, suitable for mounting an axle set of brake calipers with pre-burnished pads and rotors (the burnishing was accomplished on a separate inertia dynamometer). The calipers were mounted on fixture plates which transmitted torque from the calipers to shafts mounted on ultra low-resistance bearings, and then to sensitive load cells (one on each end) capable of resolving drag measurements down to approximately 0.05 Nm per side. These assemblies were mounted on tailstocks in turn mounted on precision sliding

rails, with a hand-cranked machine power screw for adjusting the tailstock axial position relative to the rotor.

Under 'normal' test conditions, the tailstock is positioned to center the rotor properly within the caliper, and then locked down with large diameter bed-plate type bolts. However, for the purpose of this study, the tailstocks were kept unlocked (it will be noted that there was sufficient friction in the system to keep the tailstocks in place during the drag tests). Dial indicators were placed at both tailstocks to measure their axial position relative to a baseline (centered) position. To simulate rotor movement within the caliper, the tailstocks were moved set distances, with the rotor spinning, and the effect on caliper drag was recorded.

Figure 3 and 4 below shows the test set-up. The tailstock is able to slide to the left and the right of the photograph, thus moving the caliper, the mounting fixture, and the torque sensing elements (not shown, on the backside of the tailstock) axially with respect to the rotor. This simulates the rotor moving axially with respect to the caliper in a vehicle installation:

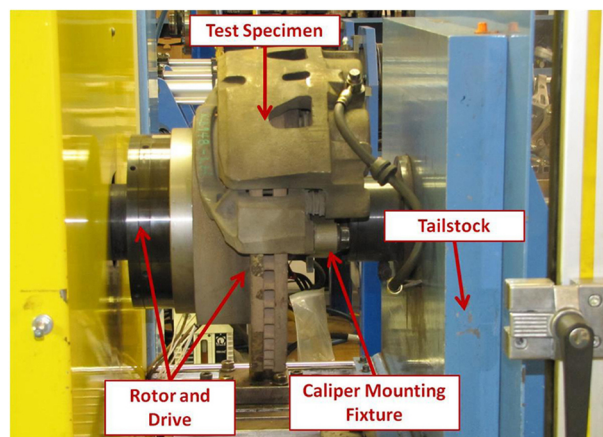


Figure 3. Component Dynamometer Drag Test Setup

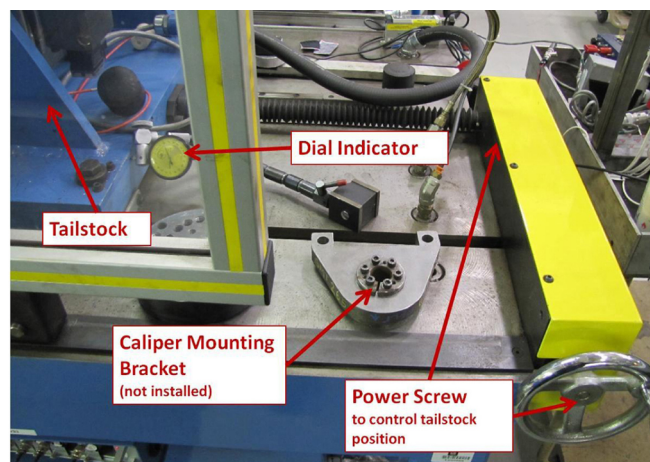


Figure 4. Detail of Drag Dynamometer showing Tailstock Axial Position Adjustment.

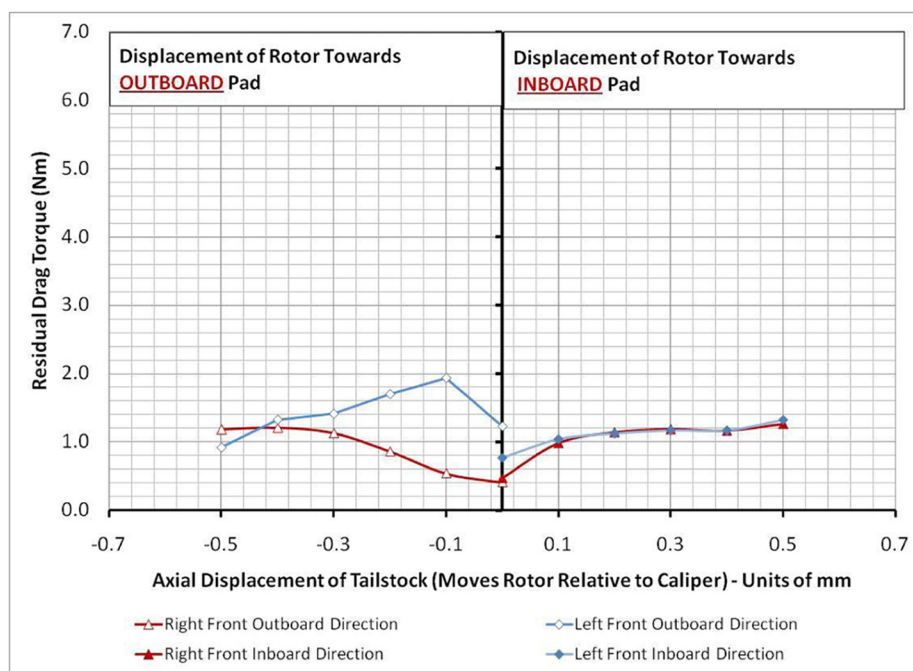


Figure 5. Drag vs. Rotor Axial Movement, Front Axle Single Piston Sliding Caliper with NAO Linings (New Caliper, New Burnished Linings)

A simple procedure was followed to map brake drag versus rotor axial movement. A baseline drag measurement after 50 bar experienced pressure was recorded first. The procedure for mapping drag vs. rotor axial displacement is summarized below:

1. Tailstock is positioned to center rotor in design position with respect to the caliper
2. Hydraulic pressure is applied to the caliper (50 bar), held for 10 seconds, and then released
3. Data recording is started
4. The rotor is spun up to the test speed of 400 RPM.
5. When the speed has stabilized, the tailstock axial position control is rotated to move the tailstock towards the rotor (thus loading the rotor against the inboard pad). The dial indicator is used to set the change in position to 0.10mm.
6. Brake drag recording continues until a total of 2 minutes of recording time has elapsed.
7. The tailstock is moved back to center, and the procedure is repeated from step 2 to step 7, changing the axial position setting by 0.1mm increments (e.g. the 2nd iteration moves the tailstock by 0.2mm, the 3rd by 0.3mm, and so on).
8. The entire procedure is repeated from steps 1 through 7, this time moving the tailstock away from the rotor (which loads the rotor against the outer pad).

Figure 5 below shows example behavior of a front axle single piston, sliding caliper with NAO linings in a new caliper, new burnished condition:

The sliding caliper in figure 5 shows drag reaching a peak at approximately 0.2 to 0.3mm of displacement. This is consistent with the following order of events (described for a typical fist-type sliding caliper):

1. the rotor starts to push back against the adjacent brake pad
2. The brake pad, which is not perfectly flat, resists at first by twisting within the spring abutment clips that restrain it, and by attempting to translate the spring clip itself axially. This resistance is highly elastic.
3. The adjacent brake pad eventually slides within its abutments and its contribution to residual force in the caliper peaks.
4. The adjacent brake pad pushes against the piston(s) or fingers (if outer pad). This force will attempt to translate the caliper housing on its guiding system. The guiding system may offer some elastic resistance (from grease and rubber sleeves or bushings, depending on design), and will eventually translate against the opposite pad.
5. The opposite pad will also resist translation by first twisting (elastically) within its abutments, and then translating
6. Residual force, and therefore drag, in the caliper will peak when both pads have been fully translated within their abutments. It should be noted that since the first pad contacted by the rotor may be fully sliding, and decreasing in friction by the time the opposite pad is pushed against, that

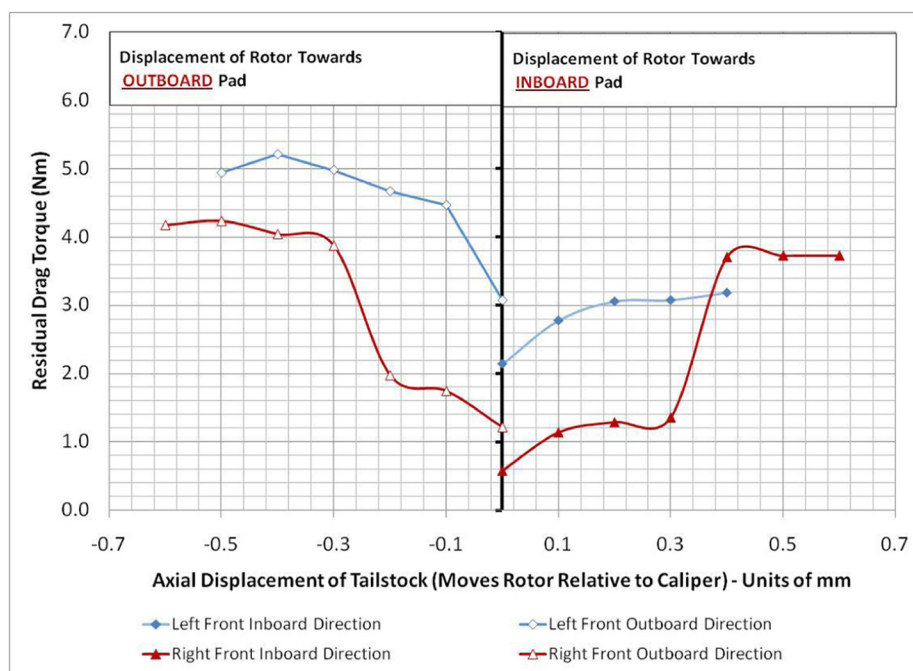


Figure 6. Drag vs. Rotor Axial Movement, Front Axle Single Piston Sliding Caliper with European Low-Met Linings (New Caliper, New Burnished Linings)

contact with the opposite pad will not always increase drag significantly.

The elastic movement of a new brake pad within its abutment clips (before full translation) is typically on the order of 0.1 to 0.2mm. Drag increases by up to 250% (from 0.4 Nm to 1.2 Nm).

Figure 6 shows a very similar front axle single piston sliding caliper with European low-met linings, in a new caliper, new burnished condition:

With the left front caliper of this example, the transition from the rotor pushing on one pad, to pushing through into the other pad and through the guiding system is quite apparent. Higher friction levels of the pads against the rotor, and higher levels of taper wear (which in turn encourage more elastic rotation of the pad within its abutments prior to translation) allow drag levels to increase considerably more than the NAO lining caliper example. Drag increase from a low of 0.6 Nm to a high of 3.8 Nm on the same caliper - an increase of more than 600% with only 0.4mm of rotor movement. The significant increase in drag on the right front caliper around 0.2 to 0.3mm - which corresponds to an increase in residual force in the pad/rotor interface on the order of 50-80N - may have occurred due to the residual forces in the caliper creating a torque load on the guide pins and increasing the friction in these interfaces, or high latent slide forces in the guiding mechanism.

It follows intuitively that conditions such as corrosion of the pad slides will cause the sensitivity of caliper drag to rotor axial movement to increase considerably. Measurements were made on a front axle single piston sliding

caliper with NAO linings after the parts had been conditioned by vehicle durability testing simulated 10 years of field exposure. Results are summarized in figure 7 below:

Drag in the right front corroded caliper increased from a centered condition of approximately 2.0 Nm to a peak of 6.6 Nm at 0.5mm rotor displacement towards the outboard pad. The left front caliper showed a small increase in drag with rotor movement off-center (from about 4.4 Nm to a peak of about 4.8 Nm when moved in the outboard direction), but was much less sensitive to rotor movement - this is likely because there was some elastic energy captured from the brake apply in the pad and backing plate, that was not fully released when the brake was released and instead reacted against the high forces that could be supported in the corroded pad slide area.

The fixed caliper is especially sensitive to rotor movement, as there is no sliding mechanism to accommodate it. As the rotor is displaced towards one or the other pad, the pad will move against the pistons and then against the highly elastic piston seals. This particular caliper (data shown in figure 8 below) operated at extremely low drag levels (0.2 to 0.8 Nm) when centered, but this drag increased to as high as 7 Nm with rotor movement on the order of 0.5mm. One test (the left hand caliper with the rotor sliding towards the outboard pad) reached a peak at approximately 0.4mm of rotor displacement; at this point drag had increased from 0.8 Nm to 5.6 Nm, or about 700%.