

Vehicle Level Brake Drag Target Setting for EPA Fuel Economy Certification

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ABSTRACT

The strong focus on reducing brake drag, driven by a historic ramp-up in global fuel economy and carbon emissions standards, has led to renewed research on brake caliper drag behaviors and how to measure them. However, with the increased knowledge of the range of drag behaviors that a caliper can exhibit comes a particularly vexing problem - how should this complex range of behaviors be represented in the overall road load of the vehicle? What conditions are encountered during coastdown and fuel economy testing, and how should brake drag be measured and represented in these conditions? With the Environmental Protection Agency (amongst other regulating agencies around the world) conducting audit testing, and the requirement that published road load values be repeatable within a specified range during these audits, the importance of answering these questions accurately is elevated. This paper studies these questions, and even offers methodology for addressing them. It includes a review of how variation in brake drag can affect fuel economy and carbon emissions certification, a review of the many transient and driver-dependent behaviors and operating conditions that can affect drag at a vehicle level (and means of measuring them) and then offers a methodology (based on probabilistic modeling) for predicting the range of drag that can be encountered in fuel economy testing. In the course of developing the methodology, a significant database of vehicle level brake drag measurements is analyzed, and a case study vehicle is used to show correlation in a "walk" from component level to vehicle level caliper drag behavior.

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INTRODUCTION

A seemingly reasonable question is often asked amongst brake engineers in the past few years - why, if it is such a small part of overall energy losses in the vehicle, has brake caliper drag received such an incredible amount of attention and research lately? Thoughtful review allows some realizations to surface - reducing caliper drag remains one of the most cost effective means of reducing road load and improving fuel economy of anywhere in the vehicle, and caliper drag is an appreciable source of variation that can affect whether a vehicle meets its published road load target when audited by a regulatory entity such as the EPA. These two factors, in addition to the many considerations internal to the brake system (such as off-brake disc wear and judder, loss of lining life [10], and increased brake dust), give importance to the cause of reducing and controlling brake drag commensurate with the attention that it has received.

This paper will begin by examining the role of brake drag on fuel economy and carbon emissions, using case study vehicles and also hypothetical "fleet" calculations to show these effects in [section 1](#). It will then discuss how variation in brake drag can affect variation in road load in [section 2](#). [Section 3](#) will review some of the methods for characterizing brake drag in the industry, and then [Section 4](#) will explore then many potential causes for brake drag variation during certification testing, including driver dependent, transient, and vehicle integration-driven effects, and also give brief discussion of methods to quantify them. [Section 5](#) shows analysis of a large database of

vehicle level brake drag measurements. [Section 6](#) will show a statistical method (Monte Carlo simulation) for predicting brake drag during certification testing. Finally, [section 7](#) will present summary, conclusions, and offer thoughts on future research.

The structure of the paper is shown again in list form below, for the reader's convenience:

1. Effect of brake drag on fuel economy and carbon emissions
2. Fuel economy certification and role of brake drag
3. Industry Methods of Characterizing Brake Drag
4. Factors affecting brake drag during certification
5. Analysis of Vehicle Level Brake Drag
6. Statistical method for predicting brake drag during certification testing
7. Summary, Conclusions, and Next Steps

SECTION 1. EFFECT OF BRAKE DRAG ON FUEL ECONOMY AND CARBON EMISSIONS

A good starting point to understand the role of brake drag in fuel economy and carbon emissions certification is to see the effect of a unit of drag improvement - most often measured as torque and represented in Nm - on fuel economy. In the United States, fuel economy is represented as the number of miles that can be travelled per gallon of

fuel burned; however, grams of carbon emissions (carbon dioxide, or CO₂) released per kilometer travelled has a linear relationship to energy efficiency and is used in many other parts of the world.

Using a highly detailed vehicle and powertrain model (employed by GM to estimate fuel economy, carbon emissions, and drive ability behaviors), it is possible to see the effect of a unit of brake drag on fuel economy and carbon emissions. The Simulink® based tool models the road load of the vehicle with a 3-term quadratic relationship between load required to move the vehicle forward versus speed (this method is consistent with SAE J2263 recommended practice [13]). Brake drag is generally incorporated into the constant term of this road load model (however, if a reliable speed-sensitive behavior was observed in brake drag, it could of course influence the linear and/or exponential terms as well). For purposes of this example, a B-segment vehicle with a composite fuel economy rating that would meet model year 2020 US mandates (about 41.7 mpg combined or 182 grams CO₂/mile, see [11]) was analyzed and drag was subtracted from the constant term only. For this relatively high efficiency vehicle, an improvement of 0.17 mpg per 1 Nm total drag reduction (1 Nm per brake corner, or 4 Nm total, would be worth 0.68 mpg). As vehicles approach the 2025 mandate levels of fuel economy, the Nm drag to mpg sensitivity will increase even further.

One of the observations made in the introduction was that brake drag remains one of the most cost effective means of improving fuel economy. The dollar value that individual vehicle manufacturers are willing to pay to fund fuel economy improvements is of course a highly proprietary figure; suffice it to say that it exists and is often program-specific. Fortunately, there is publicly available literature from which the value of fuel economy improvements can be derived (again, this does not represent what various OEM's use to represent the value of fuel economy improvements, but can at least accustom the reader to the right order of magnitude). Two studies which perhaps span a reasonable range are the NHTSA Preliminary Regulatory Impact Analysis of the new fuel economy regulations for MY 2017-2025 [4], which tended to support the new regulations, and a critique commissioned by the National Automobile Dealers Association [5], which tended to oppose the new regulations. The NHTSA study estimated a value to the consumer of increasing fuel economy from 34.1 mpg (2016 value) to 49.6 mph (2025 value) of \$6,000 per vehicle, at a cost of \$1,900 per vehicle. This would value fuel economy increases at around \$122 per mpg improvement to the manufacturer (looking at the cost to implement technology to meet the regulations as the driver for design content in the vehicle). The NADA study estimated that the value of the fuel economy improvements to the customer would only be \$1,500 per vehicle, but would cost \$3,000 to implement. Again taking the regulations as a given, and looking at the cost to the manufacturer as the driver of design content, this study would value fuel economy increases at around \$194 per mpg improvement.

In terms of grams of CO₂ per km, the US regulations are equivalent to an improvement from 160 grams CO₂/km in 2016 to 110 grams of CO₂/km in 2025. The range of valuation of carbon emissions reduction from the two cited studies is between \$38 and \$60 per gram of CO₂ per km improvement.

Returning now to the case study B-segment vehicle meeting 2020 regulations, and the 0.17 mpg per 1 Nm total drag reduction, and combining it with the above data - we see anywhere from a \$20.74 to \$30.98 value of 1 Nm of brake drag reduction. Multiplied by two for an axle set or 4 for a vehicle set of brakes, the value of reducing 1 Nm of drag in a single caliper is in truly interesting territory, and explains the first-name basis relationship many brake engineers enjoy with their colleagues responsible for fuel economy.

There are ramifications of brake drag beyond simply balancing the vehicle for fuel economy as cost effectively as possible - there are some potential certification impacts, having mainly to do with the high level of variation possible with brake drag. For this topic, we move into the next [section 2](#).

SECTION 2. FUEL ECONOMY CERTIFICATION AND THE ROLE OF BRAKE DRAG

The Environmental Protection Agency (responsible for setting fuel economy regulations in the United States, and for auditing compliance to published fuel economy ratings) published an advisory letter in 2015 to clarify automobile manufacturer's responsibilities when determining road load for a production vehicle, and also to set the allowable tolerances for road load audits [1]. According to this advisory letter, the measured road load energy loss during the city (FTP) cycle of the test can vary by a maximum of 10% from the published (certification) value, and the measured road load energy loss during the highway (US06) schedule can vary by a maximum of 7%. Variation during an audit of higher than this allowed amount will be presumed by the EPA as the road load used for certification being "substantially unrepresentative" for the entire affected production vehicle population. This would drive the manufacturer to either revise their road load (and potentially affect their fuel economy label) to the audit value, or provide additional vehicles for testing with the best case scenario being that the average of all appropriate production vehicles would be used for the revised road load specification. The EPA is very clear in this letter as well that the 10%/7% tolerance does not comprise an allowance, but rather, it is intended to allow for the combination of test to test and vehicle to vehicle variation. The expectation is that if a sufficient number of vehicles is tested, that the road load be very close to the published specifications. It follows readily - even to the layperson, that the task of determining the road load specification accurately in the face of all of the potential sources of variation, is a very serious one.

In 2012, the Netherlands Organization for Applied Scientific Research published a paper with the aim of exploring the gap between type approval (published) and "real world" fuel economy [3]. This highlights the fact that the concern over variation in road load from published values is indeed a global one. It also published measured road load coefficients for 6 relatively high fuel efficiency vehicles. The most efficient gasoline-engine vehicle tested (certified to Euro-5 emissions standards) was a 2009 model year hatchback, with a 55 kW engine, achieving 110 grams CO₂/km (49.6 miles per gallon equivalent), and the least efficient was a 2009 diesel sedan.

with a 160 kW engine, achieving 184 grams CO₂/km (29.7 miles per gallon equivalent). The 3-term quadratic road load coefficients (load = $a + bV + cV^2$) of these two vehicles were:

Hatchback: $a=80\text{N}$, $b=0.38\text{ Nh/km}$, $c=0.030\text{ Nh}^2/\text{km}^2$
 Sedan: $a=157\text{N}$, $b=0.62\text{ Nh/km}$, $c=0.030\text{ Nh}^2/\text{km}^2$

Although brake drag can exhibit strong speed dependency [6], its effect on road load is most often modeled as speed-independent on account of it being small in magnitude compared to tire or aerodynamic losses. With this strategy, brake drag adds directly to the “a” coefficient. For a small car with a relatively small wheel (280mm static load radius), 1 Nm of brake drag would add 3.6N to the road load (and 1Nm of drag at each brake, or 4 Nm total, would add 14.3 N of road load). Figure 1 shows the relationship between the energy consumption during the FTP and the US06 EPA fuel economy cycles and an increase in brake drag (expressed in Nm of drag per caliper, which is multiplied by 4 to compute the impact to energy consumption). The relationships are shown for both the above mentioned hatchback and sedan examples (the hatchback was assumed to have a tire rolling radius of 280mm, and the sedan a rolling radius of 305mm).

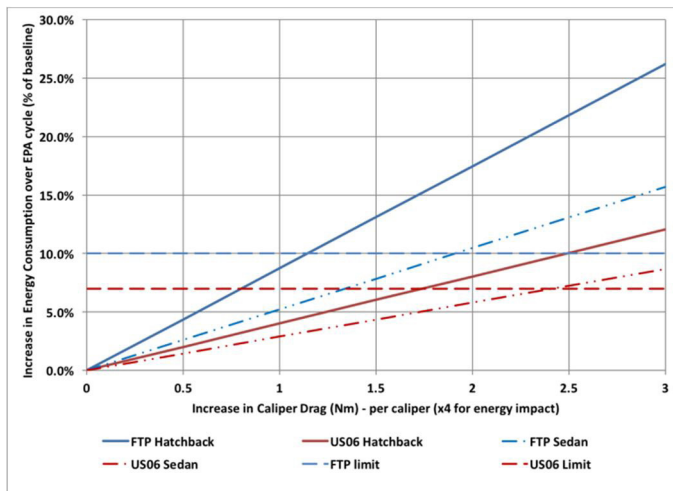


Figure 1. Increase in Energy Consumption over EPA fuel economy cycles versus per caliper increase in brake caliper drag for two example vehicles

Figure 1 shows some interesting realizations - first, with a small, fuel efficient vehicle, an increase in brake drag of only about 1.2 Nm per brake corner is enough for brake drag to consume the entire road load energy consumption allowance for FTP (this same allowance also needs to accommodate variation in tire rolling resistance, variation in aerodynamic drag, and variation in driveline losses). An increase in drag of about 1.9 Nm is enough to consume the entire energy consumption allowance for US06. It is also of interest to note that with the larger, less efficient vehicle, with a larger a-coefficient of road load, that energy consumption is less sensitive to brake drag (needing about 1.8 and 2.4 Nm to reach the FTP and US06 thresholds, respectively).

It should be noted at this point that an increase in brake drag of this amount would not necessarily cause a vehicle to fail a fuel economy audit, because variation in the other sources of road load can accommodate the brake drag increase if they operate below the

certification value (but can of course work the other way and cause an even lower threshold of what can be tolerated). However - this certainly illustrates strongly how variation in brake drag can play a significant role on complying with a published road load value. It should be noted as well that certain mechanisms for increasing brake drag (such as a high pressure brake apply, or elevated taper wear due to brake duty cycles prior to coast down testing) will tend to affect all four brake corners at the same time.

After a brief review of methods of measuring brake drag in section 3, these mechanisms for increasing brake drag, along with several others, will be covered in more depth (in section 4).

SECTION 3. INDUSTRY METHODS OF CHARACTERIZING BRAKE DRAG

There are several methods used for measuring and characterizing brake drag behavior in the automotive industry (amongst OEMs and suppliers). Most are done at a caliper component or brake corner subsystem level, on purpose-built drag test rigs, component dynamometers, or inertia dynamometers. Figure 2 is a photograph of a typical high speed residual drag dynamometer. Machines such as this generally mount the brake disc on a rotating spindle, capable of reaching rotational speeds equivalent to highway speeds or higher, and the caliper on a separate spindle. The caliper spindle reactions load through low friction bearings, into a very sensitive load cell capable of resolving drag down to 0.05 Nm or less.

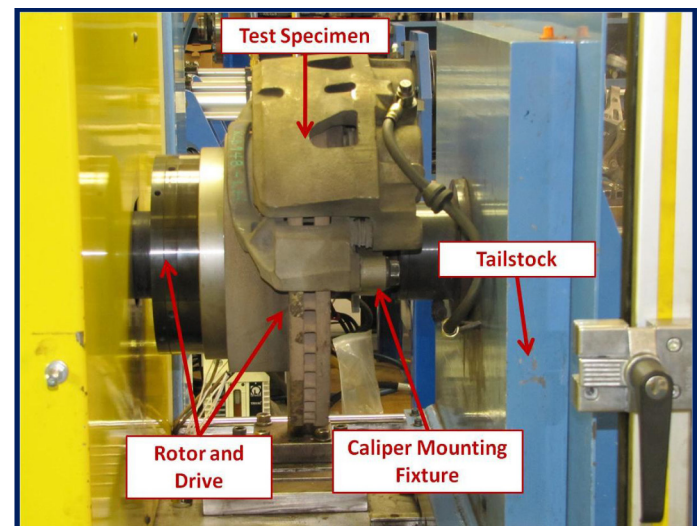


Figure 2. Typical high speed residual drag dynamometer

Some companies rely mainly on vehicle level measurements, using rolls (chassis) dynamometers [8]. Chassis dynamometers suitable for measuring brake drag will generally have torque cells placed close to the road-simulating drum, thus minimizing or eliminating the losses due to the support bearings for the drum and drive mechanisms.

Vehicle level measurements have the advantage of capturing most of the potential integration issues (such as bearing sag, caliper to rotor mis-alignments due to build tolerances, and the effect of component deflections due to absorbing vehicle loads and braking loads).

However, they are generally not very accurate as caliper drag must be separated from bearing and tire losses, and load cells suitable for

absorbing braking and tractive loads will operate at the very low end of their range when measuring residual drag). Typical vehicle level caliper drag measurement resolution will be coarser than component level measurements, requiring considerable care to get below 1.0 Nm. Figure 3 shows a photograph of a typical chassis dynamometer.

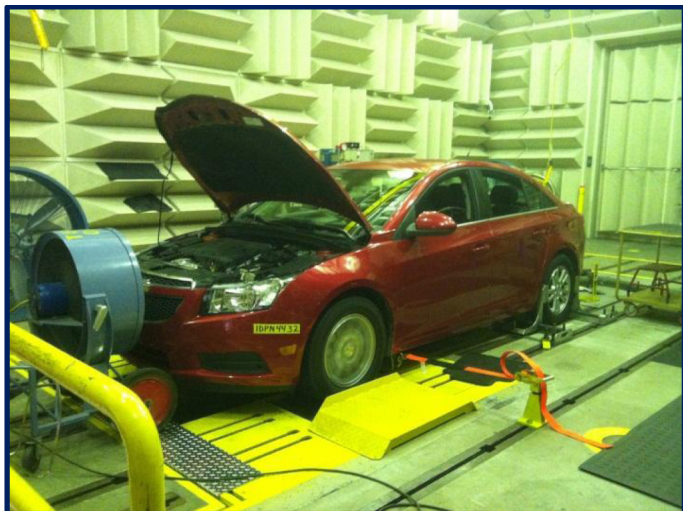
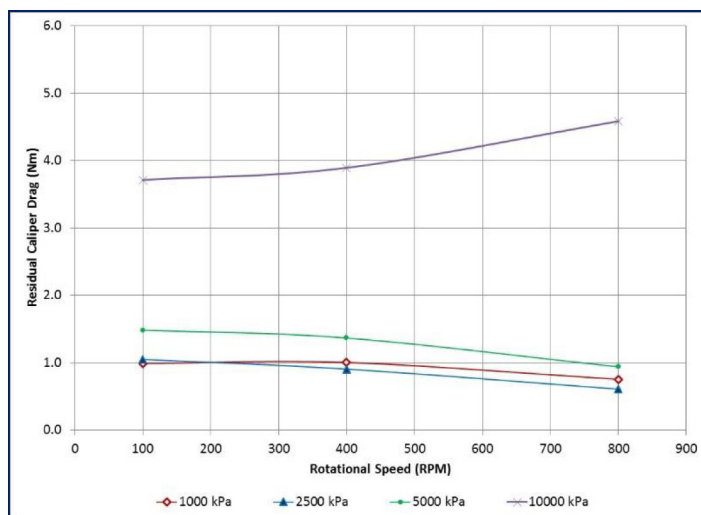
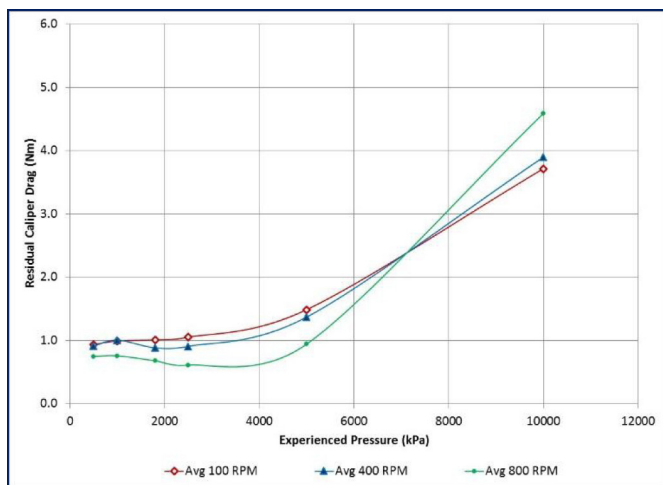


Figure 3. Typical single-axle chassis dynamometer

With seal and seal groove tuning (one of the most important engineering activities in caliper design that affects drag), and determination of the pad configuration still being highly empirical and highly iterative, it is reasonable to believe that the vast majority of caliper engineering for brake drag occurs at the component level, where testing is much easier to set up, much quicker to run, significantly more accurate, and can occur much earlier in the vehicle development process.

It is common in the industry to measure caliper drag versus experienced pressure, often at multiple speeds. Figure 4a shows an example of drag versus pressure (with a visible “knee point” where running clearance transitions to zero somewhere between 5000 and 10,000 kPa), and figure 4b shows the same data in a drag versus speed format (data are from competitive benchmarking of an undisclosed vehicle).



Figures 4a (above) and 4b (below). Example of residual drag versus experienced pressure (4a) and the same data versus speed (4b). Data from competitive benchmarking.

SECTION 4. FACTORS AFFECTING BRAKE DRAG DURING CERTIFICATION

Simple examination of some of the example data in section 3 reveals the quandary - brake caliper drag shows a rich variety of behavior, and its magnitude can vary by a factor of 10 or more, depending on the test conditions and pre-conditioning of the brake materials. Overall, there are many factors outside of the design parameters of the caliper that can affect brake drag. This section will briefly examine several of them, touch on how they can be measured or observed, and discuss their potential role in fuel economy certification. It should be noted that there are other sources of brake drag that generally occur outside of the realm of normal, low mileage use (including integral parking brake over-adjustment, extreme taper wear and high temperature operating conditions, heavy corrosion on moving parts, or damage to brake corner components). With the focus of this paper being on factors that can affect certification, only sources of drag that have a reasonable chance of occurring during certification testing are addressed here. To maintain some semblance of order, this section will be broken down into sub-sections for each phenomenon discussed, with the content summarized in the list below:

- 4 a. Drag due to higher pressure brake applies
- 4 b. Drag due to elevated taper/cupping wear of the pads
- 4 c. Drag due to pneumatic effects
- 4 d. Drag due to parking brake cables
- 4 e. Drag due to parking brake applies
- 4 f. Drag due to bearing deflection
- 4 g. Drag due to Rotor Lateral Runout

4a. Drag Due to Higher Pressure Applies

The tendency of the brake caliper to show increased drag after experiencing high service brake pressures is perhaps one of the most well known effects on brake drag. It is caused when the retraction of the caliper piston(s) by the seal(s) is less than the deflection of the

caliper housing and compression of the brake pad, resulting in the pads and housing pushing the piston back against the piston seal when the brake is released. This mis-match of retraction to piston movement during the apply commonly occurs when piston travel reaches a point to where the seal can no longer travel with it - the seal slips, releasing much of its stored elastic energy and ability to retract the piston, and the piston retracts less than it had moved on the apply. One of the few published detailed analytical studies on caliper seal behavior was done by Anwara can be found in [9] - this is worth consulting for readers not familiar with this behavior.

It is also true that once a higher drag condition is set in the brake caliper, it can remain persistent even with additional brake applies. Previous research by the author [7] has shown that on-road, caliper residual forces can remain surprisingly elastic - meaning that road inputs (vibrations) will generally only partially relieve an elevated drag condition.

A high drag condition set with high pressure applies can remain over a driving cycle. One may reasonably hypothesize that "normal", repeated lower pressure brake applies can help ease the seal back into a normal running clearance position through movement of the piston and hydraulic pressure behind the seal encouraging it to move forward towards its "normal" position. Drag behavior over repeated applies and driving cycles remains an area sparsely covered in the literature. In the author's experience, recovery after setting a high drag condition with a high pressure apply is a relatively slow and not entirely reliable phenomenon. Figure 5 below shows real-time drag (averaged over each "mini-trip") versus time measured over a simulated FTP (EPA-specified) driving cycle for a single piston sliding caliper, as measured on a high speed component dynamometer. There are 4 traces of drag and one trace showing speed (which was the same for each run). Each trace represents running an identical FTP simulation on a high speed drag dynamometer, and differs only by a single brake apply of differing pressure at the start of the run. It should be noted that the drag dynamometer was capable of only static applies, so braking pressure (appropriate for the deceleration of the braking event) was applied in between the many "mini-trips" in the schedule at which the vehicle comes to rest:

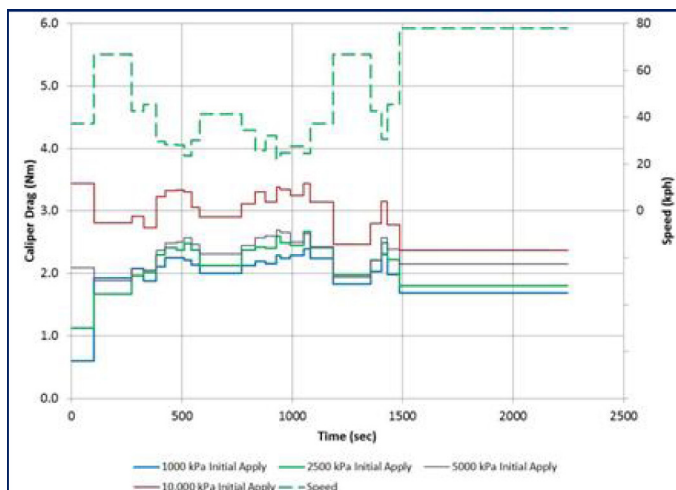


Figure 5. Example Residual Caliper Drag vs. Time over Simulated FTP Driving Cycle (measured on high speed drag dynamometer)

The drag levels for the three lower starting pressures (1000, 2500, and 5000 kPa) came together quickly (within the 1st braking event) and tended to stay within 0.5 Nm of one another, and often much closer. The drag levels for the run starting with 10,000 kPa remained higher than the rest by 0.6 to over 1.0 Nm for most of the run - only towards the end did drag start to return to the levels consistent with lower experienced pressure.

This factor is perhaps one of the most persistent risks for actual brake drag realized during a coastdown test differing from a target defined for certain conditions. The brake usage for a test vehicle is not rigorously controlled (nor should it be), and furthermore, even a driver that is careful to avoid unnecessarily forceful braking tends to lose most sensation of how hard he or she is pressing on the brake pedal when the vehicle is stationary. Time-history measurements of braking pressure of vehicles undergoing fuel economy testing at GM have shown anywhere from 3500 kPa to close to 9000 kPa pressure - and the peaks invariably occur when the vehicle is stationary!

4b. Drag Due to Elevated Taper/Cupping Wear of the Pads

A perennial source of brake drag variation is the constant changing of the brake pad shape and surface profile due to wear of the pad material, which can promote uneven wear in the form of taper angles and "cupping" or "doming" wear under the piston(s)/fingers. Wear profiles are beholden to the usage history/duty cycle, which in turn is governed by driver behavior, and for public road tests, by surrounding traffic behavior. Recalling the EPA advisor letter [1] referenced in section 2, vehicles are conditioned for certification testing with 4,000 to 6,200 miles of driving. This represents use far beyond the typical FMVSS-defined 200-stop burnish used as conditioning for many brake tests in the industry. It is also long enough so as to become positively onerous to condition brake friction material in any large quantity for development activities, a situation that heavily promotes use of some form of accelerated conditioning procedure.

When brake wear is accelerated, it is usually done by increased braking temperatures, higher braking speeds, and even higher pressures.

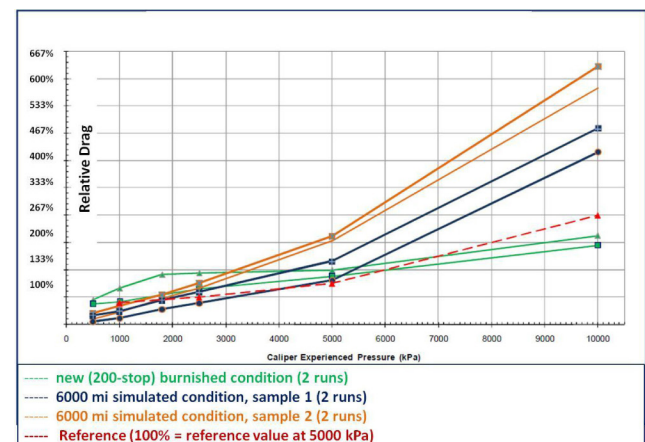


Figure 6. Example front caliper drag in new burnished condition at 400 RPM (1 sample) and simulated higher mileage (6000 mi) condition (2 samples)