

Methods for Sizing Brake Pads for High Performance Brakes

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ABSTRACT

An aspect of high performance brake design that has remained strikingly empirical is that of determining the correct sizing of the brake pad - in terms of both area and volume - to match well with a high performance vehicle application. Too small of a pad risks issues with fade and wear life on the track, and too large has significant penalties in cost, mass, and packaging space of the caliper, along with difficulties in maintaining adequate caliper stiffness and its impact on pedal feel and response time.

As most who have spent time around high performance brakes can attest to, there methods for determining minimum brake pad area, usually related in some form or another to the peak power the brake must absorb (functions of vehicle mass and top speed are common). However, the basis for these metrics are often lost (or closely guarded), and provide very little guidance for the effects of the final design (pad area) deviating from the recommended value.

This paper proposes methods, justified with dynamometer and vehicle test data, to determine brake pad area (based on considerations for fade performance), and brake pad volume (based on considerations for wear life), for high performance brake systems designed for high speed, closed loop race track operation. The methodologies are geared towards "high performance street" friction materials.

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INTRODUCTION

Despite the relentless pressures for improving fuel economy and reducing emissions, modern high performance vehicles are achieving the highest performance levels in automotive history. Bolstered by powertrain technologies such as direct-injection, forced induction, and highly efficient transmissions, tire and suspension technologies to extend grip to previously unheard of levels, and further advances in aerodynamics, many turn-key high performance production vehicles differ very little in capability from their full-race siblings.

As impressive as 600-plus peak horsepower sounds under the hood of a performance car - the brake engineer quietly contends with the fact that an average braking event at the end of a high speed straight will force a single front brake to absorb well over 2500 peak horsepower, and the brake system overall will repeatedly need to absorb average power loads of 1800 hp or more.

Facing the knowledge that an approximately 12 kg chunk of iron (brake disc) and a few hundred grams of one of friction material are responsible for hauling down a 2000+ kg vehicle from 70-plus meters per second - the brake engineer knows that there is little room for error. He or she also knows that the components must be designed to withstand these conditions repeatedly, sometimes over dozens of laps and multiple tanks of fuel.

This paper starts with some optimization exercises designed to show the drawbacks of having too large of a brake pad, thus emphasizing the importance of optimal sizing. It then proposes two separate methodologies for sizing brake the brake pad - one of which relates brake fade behavior to pad area, and the other relating pad volume to its life on the race track. Together, these methods provide an objective means of optimizing the brake pad size. Both methods are confirmed with vehicle testing.

The sections noted below show the organization the reader may anticipate:

1. Why Optimal Pad Sizing is Important
2. The role of pad area in brake fade - theory
3. Pad Sizing for Fade Considerations
4. Brake Pad Wear in Race Track Conditions
5. Method for Sizing Pads based on Life Prediction
6. Validation with Vehicle Tests
7. Summary and Conclusions

WHY OPTIMAL PAD SIZING IS IMPORTANT

The packaging demands of the tire/wheel assembly, as well as effects such as the loads they impart to the rest of the vehicle, gives them profound influence over the vehicle design. Tire (and therefore wheel) sizing is usually determined, and locked down, very early in

the development of a new high performance vehicle, and has significant tradeoffs in traction, unsprung mass, and packaging if changed [7]. This puts the wheel in the position of being an “archnemesis” to the brakes in their competition for packaging space. The industry standardization of tire sizes, and tire to wheel interface geometry leaves very little opportunity for affecting the space that the brake can occupy. The brake engineer must determine how to allocate this space between the brake rotor, and the brake caliper bridge. There exists a conflict between two aspects of performance that are both important to a high performance car - the thermal storage and cooling capacity of the brake rotor, which is very sensitive to the rotor outer diameter and affects almost every aspect of brake performance (including fade and fluid temperatures), and the stiffness of the brake caliper, which affects pedal travel, taper wear, and mechanical efficiency.

The tradeoffs associated with larger pad sizes can be realized in multiple ways, depending on the brake corner design strategy. Since this paper is focused on the methodology for sizing brake pads, and can afford to dwell only briefly on the why, the tradeoffs are briefly illustrated with two simple optimization studies.

Figure 1 was generated using a simple beam model of caliper stiffness, and shows the change in pad and caliper assembly mass as pad area is changed. The caliper was aluminum, opposed piston construction, and the housing geometry was adjusted to maintain constant stiffness as the pad area (holding a constant aspect ratio) increased (which pushes the center of clamp load further and further from the bridge).

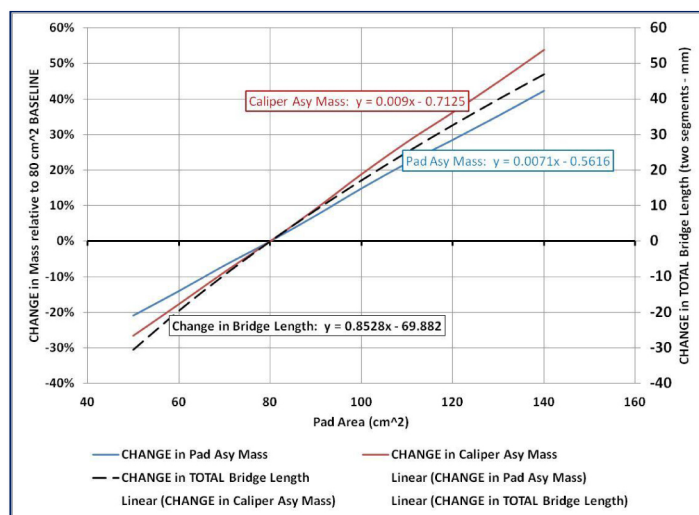


Figure 1. Effect of Pad Area on Pad and Caliper Assembly Mass (constant rotor size; caliper stiffness maintained by increasing bridge length - relative to 80 cm² baseline)

With further acknowledgement of the very approximate nature of the highly simplified models used - there is about a 1% change in assembly mass per cm² change in pad area, and about a 0.7% change in the mass of the pad assemblies per cm² change in pad area. Of potentially greater importance in some situations, the

tangential length of the caliper increases by about 0.9mm per cm² pad area and can affect tangential packaging space (often critical for clearance to suspension and steering links).

Figure 2 shows a series of case studies illustrating some of the tradeoffs between pad area, rotor diameter, engine power bandwidth (related to the rotor size and swept area), and pedal feel (related to the effect of pad size on caliper stiffness). The engine power bandwidth is the maximum power engine that the brake system can be fitted to (keeping the same brake cooling environment) before exceeding an internally specified temperature threshold for the “Auto Motor Und Sport” high speed fade test. The baseline case is an “optimal” caliper stiffness and smaller rotor (by 5mm). Case 2 (second from left) keeps the same pad area but increases the rotor outer and inner diameters by the same amount (5mm), and cutting down caliper bridge thickness. This increases the theoretical bandwidth of the brake system, at the expense of caliper stiffness and pedal feel. Cases 3 keeps the same rotor outer diameter, but moves the inner diameter inward to increase the pad height and therefore the swept area. The pistons move inward to maintain centering with respect to the pads, and the caliper loses additional stiffness (which is now becoming very noticeable for pedal feel, at about a 4mm travel increase). Case 4 maximizes the pad area and swept area for the rotor OD, but pedal travel increases about 6mm.

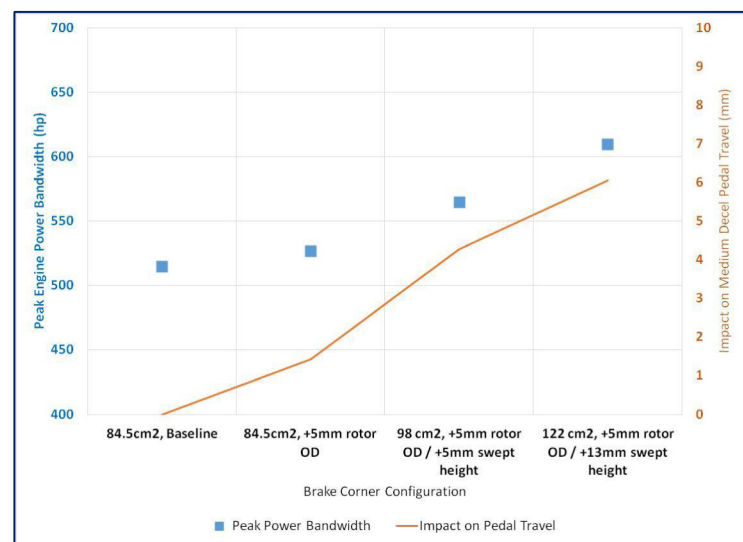


Figure 2. Case studies showing relationship between pad area, engine power bandwidth, rotor size, and pedal feel

THE ROLE OF PAD AREA IN BRAKE FADE - THEORY

Brake fade is the loss of output (apparent friction), usually coupled with increase in fluid consumption (affecting pedal travel) that occurs when the brake is operated at elevated temperatures, speeds, and deceleration loads. The physics of brake fade, how it progresses, and the potential role of pad area in fade are inseparable from the physics of the friction process in general - which remain quite complex and elusive to a full, predictive understanding. Fortunately, the friction

processes in automotive brake linings have been studied extensively over the past 5-6 decades, generating many notable publications which can in turn support theory relating fade to brake pad area.

There is wide support in literature [1, 13, 14] for some common observations for how the friction process changes with elevated temperatures and the onset of fade:

- As temperatures increases, the materials providing cohesiveness of the friction material matrix (such as phenolic resin) lose strength, which allows structural, load-supporting particles in the matrix such as metallic fibers, and metallic or ceramic chips, to become more easily dislodged.
- Certain structural materials, such as metallic particles, will lose strength with elevated temperatures and be more prone to fatigue fracture. The surface microstructure of the brake disc also loses strength and also offers less resistance (less friction) to abrasive ploughing by lining structural particles.
- Wear of both the lining and disc increases with temperature, exponentially in some cases. The increased availability of material flow, which can compact and even sinter on the friction surfaces, can lead to a thick tribo-film on one or both surfaces (sometimes known as “glazing”).

During high energy operating conditions, the friction interface experiences a wide range of operating conditions due to non-uniformity in the temperature and pressure distribution. Fade is usually progressive, and almost certainly also non-uniform over the friction interface [8, 9]. As a high energy, high temperature braking event progresses, small regions of the friction interface can become extremely hot, and lose enough structural integrity to fully “saturate” (saturation refers to the state in which the maximum frictional force the region is capable of is being produced is generated, and any additional clamp force does not produce additional frictional force). Continuation of the braking event, or subsequent braking events, can cause saturation to progress, covering more of the friction interface area.

It is this concept of “saturation” through which the most intuitive form of friction sensitivity to brake pad area is introduced. For the most part, larger pad area reduces area of saturation and increases the net friction level. There are some competing effects, however - it is more difficult in the caliper design to achieve a uniform pressure distribution as the pad becomes larger; in braking conditions where non-uniformity in the pressure distribution is severe, a larger pad can actually lead to a lower net friction level.

There is generally a ‘sweet spot’ in the operating temperature range where friction is maximized; for most street-able, track capable brake linings this occurs well above everyday driving operating temperatures (300-500 deg C friction peaks versus 100-200 deg C daily driving temperatures). Figure 3 shows minimum and average apparent friction versus temperature averaged across a range of braking speeds and pressure levels for a typical street-able, track capable lining.

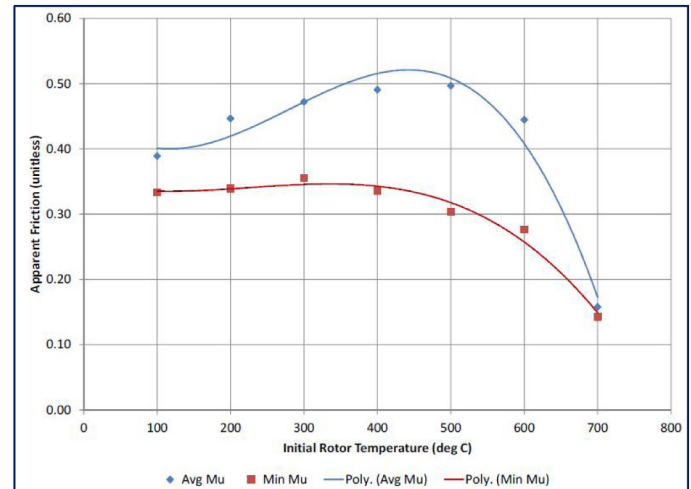


Figure 3. Minimum and Average Apparent Friction versus Temperature (averaged across range of braking speeds and pressures) for typical low-met, track capable lining material

It is logical to believe that this temperature “sweet spot” exists on many scales, both in small regions of the friction surface as well as globally; indeed this is supported by tribometer tests of reduced size lining samples [2, 15, 16]. Relevant to the apparent friction versus pad area sensitivity, this behavior suggests that the “global” or net friction behavior is sensitive to the temperature distribution in the friction interface. Depending on how the pad area affects the temperature distribution in the friction interface over the duration of the braking event, the net friction behavior at a given bulk brake rotor temperatures can be affected either positively or negatively. It should be noted that the temperature distribution is usually extremely transient (time dependent), and the pad area can affect how the temperature, and therefore the friction distribution evolves over time during a braking event. The increasing average friction level in figure 3 at 500 deg C with the decrease in minimum friction level is consistent with friction behavior becoming extremely time-dependent and changing significantly over the course of the braking events.

PAD SIZING FOR FADE CONSIDERATIONS

The first of the two main considerations for sizing the brake pad for high performance vehicle applications is that of fade behavior (the other is lining life on the track). Previous work [11] suggested that a combination of braking speed, dissipated braking energy, and brake rotor bulk temperature were highly effective predictors for modeling brake friction (using a neural network model at the time). By combining speed and energy into braking power, and looking at a narrow temperature range (and for all practical purposes well optimized track capable brake systems will operate in narrow temperature range for most of the duration of a track session), this creates a strong hypothesis that a relationship between braking power and friction behavior within a narrow temperature band can be found.

To prove this, a series of inertia dynamometer tests were run - the main purpose of the testing was to see if braking power normalized by pad area was a strong enough predictor of apparent friction within a temperature band to use to determine brake pad area. Two different configurations were tested with two different lining