Introduction

This document is a synopsis of SAE technical paper 2006-01-0691, by David Antanaitis and Anthony Rifici. It reflects my understanding of what the authors observed and reported in their paper. I was pleased to note that the synopsis by another SAE member, which I initially provided for general consideration, corresponds with my own understanding of this paper, and appears to be reasonably sound from a practical standpoint. I'd certainly be open to any criticism and/or correction of my own interpretation by either author. Criticisms from anybody else, not so much, so keep it to yourself, especially if you haven't read the original paper.

Where I thought they would help reduce ambiguity, I have used direct quotes to convey the precise words and phrases used by the authors in their paper, while at the same time being mindful to honor the SAE licensing agreement with respect to use of that document. Please note that the primary focus of the original SAE paper, as stated by the authors, was to "understand the mechanisms by which crossdrilling affected brake performance." Nothing more. Three different configurations were studied, two contained sliding calipers F/R (one on a performance sedan and one on a sports car), along with one system containing opposing pistons (on a high performance sports car).

The crossdrilled rotors discussed in this paper were identical to their blank counterparts in every respect, except for the crossdrill holes. In fact, it appears that they were obtained as blanks and drilled for testing, although this was not stated. Regardless, this implies that no special considerations or allowances had been made during their design or manufacturing to offset the rotor weakening and material loss produced by the drilling process. Consequently, any and all conclusions regarding the reliability and service lives of these crossdrilled rotors would, at best, be applicable to only the cheapest crossdrilled rotors on the market.

Within each of the three brake systems used, the following characteristics were examined and compared between the crossdrilled rotors vs. the blanks:

- Brake cooling
- Brake fade
- Brake output (performance)
- Wet brake output (wet performance)
- Brake wear

The SAE paper examines these properties as related primarily to one type of pad material, semi-metallic, although different semi-metallic formulations were used during testing. The authors noted that this lining material was selected because, according to the authors, it is the material type used for "most high performance street" pads. For comparison, non-asbestos organic (NAO) pads were selected for one of the brake systems, but the results obtained with those were atypical of the results obtained with the performance pads, and are mentioned in this synopsis only to provide contrast.

All the rotors used for testing were from the same supplier and featured similar crossdrilling features (hole diameter, hole density, etc). The following configurations were tested:

- **System 1:** performance oriented sedan w/ semi-metallic "high performance street" pads. Sliding calipers, 2 pistons front, single rear, curved vane front rotors, pillar block rear rotors

- **System 2:** high performance sports car w/ semi-metallic "entry level race" type semi-metallic pads, opposed pistons both front and rear, curved vane front rotors, pillar block rear rotors
- **System 3a:** high performance sports car w/ NAO pads. Sliding calipers, 2 pistons front, single rear, curved vane front rotors, pillar block rear rotors
- **System 3b:** same vehicle as system 3a, but with blank rotors smaller than the drilled rotors of 3a (4% smaller front, 8% smaller rear), presumably in an attempt to achieve equivalent rotor mass, and front pistons larger by 13%, presumably to provide braking torque equivalent to that produced by the larger diameter rotors of system 3a.

Fortunately, most testing was conducted on brake systems 1 and 2, because systems 3a/3b turned out to be something of a lame duck due to their numerous variables.

Brake Cooling

Crossdrilling improved front rotor cooling at all test speeds on both brake system 1 (w/ pillar block front rotors, instead of the curved vane design used for other tests) and system 2. The amount of improvement increased with speed. Rear rotor cooling was also improved in system 2 at all speeds by crossdrilling, but only at the highest tested speed with system 1.

For brake system 1, the average rotor cooling differences produced by crossdrilling were as follows (per axle set):

- Front axle: 8.8% improvement at 50 kph (approx. 31 mph), 12.1% improvement at 100 kph (approx. 62 mph), and 20.1% improvement at 160 kph (approx. 99 mph)
- Rear axle: 3.2% deficit at 50 kph (approx. 31 mph), 1.9% improvement at 100 kph (approx. 62 mph), and 8.5% improvement at 160 kph (approx. 99 mph)

In other words, front rotor cooling was improved at all speeds by crossdrilled rotors, with the degree of improvement increasing with speed, and rear rotor cooling was improved at speeds above business district city driving.

Several factors contributing to the lack of low-speed cooling improvement by crossdrilling the rear rotors of system 1 were offered by the authors. These included the absence of splash shields at the rear rotors, large open vent areas, and very short airflow paths.

For brake system 2, the average rotor cooling differences produced by crossdrilling were as follows (per axle set):

- Front axle: 7.8% improvement at 50 kph (approx. 31 mph), 8.5% improvement at 80 kph (approx. 49.6 mph), 10.4% improvement at 110 kph (approx. 68.2 mph), and 12.1% improvement at 140 kph (approx. 86.8 mph)
- Rear axle: 4.1% improvement at 50 kph (approx. 31 mph), 3.0% improvement at 80 kph (approx. 49.6 mph), 7.7% improvement at 110 kph (approx. 68.2 mph), and 13.4% improvement at 140 kph (approx. 86.8 mph)

To summarize, both front and rear rotor cooling were improved at all speeds by crossdrilled rotors, with the degree of improvement generally increasing with speed.

Note that the improvements in rotor cooling observed for system 2 are ***despite*** a front rotor mass reduction of 0.2 Kg (approx. 7 oz) per rotor, and a rear rotor mass reduction of 0.1 Kg (approx. 3.5 oz) per rotor due to drilling.

The authors suggest that the correspondence demonstrated between rotor cooling improvement and speed are consistent with the theory that rotor crossdrilling can increase the heat rejection capability of the rotor by increasing airflow through its vent area and reducing the overall airflow resistance of the rotor.

Brake Output Performance and Fade

Drilled rotors produced slightly lower output at low speeds, but demonstrated better temperature stability than blanks, so their output performance (stopping capability) became significantly better than blanks as speeds and temperatures increased.

The authors suggested that blanks offer better performance at low speeds and temperatures because of their greater surface area, but that as temperatures rise, the pad material softens somewhat, and is able to squish into the holes of the crossdrilled rotors, increasing the significance of the more aggressive faces of the drilled brake plates. It should be noted that racing conditions or temperatures are not required for this phenomenon to occur. The apparent friction of the crossdrilled front rotor overtakes the blank at 170C degrees (approx. 338F degrees), which is certainly not high at all. Due to the heavy front brake biasing of the test vehicles, rear rotor temps never exceeded 190C degrees, so apparent friction of the blanks was an average of 3% higher than that of the crossdrilled rear rotors throughout testing.

During high speed fade testing, the crossdrilled rotors began to produce better deceleration gain than the blanks at front pad temps of approx. 285C degrees, and the improvement increased as pad temperature rose.

The authors noted that, for brake system 1, the crossdrilled rotors produced higher overall output and were more thermally stable. These conclusions were made with regard to street performance. With respect to track performance, deceleration gain was higher over the entire temperature range for the crossdrilled rotor configuration. This deceleration improvement was observed with two different semi-metallic pad compounds that the authors claimed are “employed frequently by European automakers.”

During high performance wear testing of brake system 2, apparent friction was higher for the blank rotors during burnish and again during 450C degrees wear testing. However, the blank and crossdrilled rotors produced comparable apparent friction at 400C degrees, and the crossdrilled rotors produced higher apparent friction at all test temps from 500C through 700C degrees. Post test inspection revealed glazing over much of the surface area of the pads used with the blanks, but the crossdrilled rotors produced no pad glazing.

On the track, brake system 2’s braking performance vs. time (snub number) was examined, rather than temperature. As expected, the blanks produced better performance at the beginning of the test, but their performance degraded faster than the crossdrilled rotors, resulting in higher brake system output for the crossdrilled rotors throughout most of the test. The authors stated that, “When only the most significant braking events are looked at (figure 9 [not reproduced for this synopsis]), it can be seen that the non-crossdrilled rotor brake system started with similar (but slightly lower) output than the crossdrilled brake system, but that the output with the non-crossdrilled rotors decreased as the test progressed. Output for the high speed braking events was stable with the crossdrilled rotors."

Brake system 3 was the oddball with respect to braking performance results. A series of 20 (twenty) repeated braking events from 110 mph down to 0 mph at a target deceleration rate of 0.6G were performed with brake systems 3a and 3b, with the stops being repeated at 1-mile intervals. This was referred to as the General Motors "High Speed Abuse Test." The deceleration rate of the smaller blank rotors (system 3b) was consistently higher than that of the larger crossdrilled rotors of system 3a. Why? As you may recall, the 3a and 3b brake systems were fitted with NAO pads, rather than performance pads. Post testing inspection of these pads revealed pad decomposition in both systems. Although there was less decomposition with the crossdrilled rotors, as well as less pad glazing, it was suggested that the much more extensive pad glazing produced by the blanks had somehow reinforced the pads' shear strength in the pad-to-rotor contact areas, offsetting the negative impact of pad decomposition. Additional mechanisms were also suggested, all of which involved aspects of the NAO pad material and its decomposition. However, the moral of this story appears to be, "Stay away from NAO pad material for performance braking systems." This should be fairly easy, since most performance pads are semi-metallic, anyway.

According to the authors, all the data for brake systems 1 and 2 suggest that when brake linings are operated at high enough temperatures to lose their integrity and begin to fade, that crossdrilling provides surface features for the pad material to extrude into, resulting in an interaction "on a much larger scale than the usual inter-asperity interaction," which increases apparent friction. However, if the linings are heated to the point at which they begin to disintegrate rapidly (brake system 3), then crossdrilling will not improve fade performance, and may even reduce brake output. This further suggests that relatively non-compressible linings, particularly those that begin to decompose with increasing temperatures before experiencing any significant increase in compressibility, will not benefit much – and may actually suffer reduced fade performance – when using crossdrilled rotors.

Wet Braking Performance

Wet braking performance was tested for only brake system 1. For low pressure (and low temp) brake applications in wet conditions, apparent friction was much lower for crossdrilled rotors than for blanks. No surprise there. At higher pressures/temps, there was little difference between the blanks and the crossdrilled rotors, with the crossdrilled rotors producing slightly greater apparent friction above 200C degrees, and the blanks fairing better below 200C degrees. (Bear in mind that 200C degrees is not considered a high temperature condition for disc brake systems.) The single exception to this trend was that the blanks, "for reasons unknown," produced marginally higher apparent friction at 400C degrees. Go figure. The authors suggested that lower application pressure (only 3 m/s/s) accounted for the relatively close wet braking performance between the crossdrilled rotors and the blanks, because lower pressure probably reduces the interaction between rotor crossdrilling and pad material that tends to increase brake output.

According to the authors, test data support the theory that the brake operates in a micro-elastic hydrodynamic lubrication regime, and that crossdrilling provides an escape route for the water from the friction interface in low braking pressure wet conditions, explaining the ability to the crossdrilled rotor to keep up with the blank at lower temperatures.

However, the pads on the blanks were able to push though the water film at higher temps, negating to a large extent the advantages offered by the holes of the crossdrilled rotor and allowing the performance of the blanks to stay close above 200C degrees.

Miscellaneous Additional Test Results and Observations

Pedal feel data were analyzed during the same 15-ramp stop fade sequence used to generate brake system output data for system 1. Pedal force and travel started out at comparable levels for both crossdrilled rotors and blanks, but remained more stable with the crossdrilled rotors as lining temps increased, and the required pedal force and pedal travel were both lower for the crossdrilled rotors through most of the fade testing, while crossdrilled brake system compliance was higher. Track testing with brake system 2 produced similar results.

Although the results achieved with brake systems 3a and 3b, considering their decomposing NAO pads, hardly appear representative or even relevant, I will cite them for the sake of completeness. As expected, the blanks (system 3b) faired better with regard to both required pressure and travel. The authors suggested this was due to the reduction in pad to rotor contact area produced by the crossdrilling for lower temperatures. At higher temperatures, it was due to the reduction in pad glazing that was achieved by the crossdrilling. I suspect the larger front brake pistons of system 3b may have also been a factor. Regardless, the performance of brake systems 3a and 3b was aberrant due to pad decomposition, and therefore hardly worth mentioning.

No significant difference in compliance between the crossdrilled rotors and the blanks was observed on the track with brake system 2. However, although brake system runout was relatively mild for both rotor types, brake system runout for the blanks was 3.5 times greater than that of the crossdrilled rotors, peak runout pressure more than triple that of the crossdrilled rotors, and the length of time spent in peak runout was more than double for the blanks.

One observation made by the authors appears to suggest that those who choose to run drilled rotors may want to consider slotting in conjunction with drilling. The observation to which I'm referring is that crossdrilling results in increased pad wear in the areas of the rotor crossdrill patterns, resulting in uneven pad faces and requiring some deformation of the pad in order to bring the more severely worn areas into contact with the rotor. It has been my experience that slotting in addition drilling prevents the development of uneven pad faces at the expense of accelerated pad wear, eliminating this problem.

Introducing holes into the brake plates provides additional paths along which cooling air can travel and increases the "wetted" surface of the rotor. Slightly better rotor cooling is possible when the crossdrilled holes pass though the vanes, themselves, rather than through only the plate cheeks in the vent area, probably due to the interruption of vane airflow when the holes pass only through the cheeks of the plates.

Introducing too many air paths may be possible. Rotors exhibit temperature gradients across their faces, with the highest temps being out toward the circumference of the rotors, and the lowest temps in toward their hats. The authors reasoned this might imply the possibility of creating too many holes through the cheeks of the plates and thereby reducing airflow to the hottest rotor areas. This would result in a reduction in heat rejection capability, as evidenced by the rear rotor cooling data for brake system 1. (Of course, this possibility would not apply to holes drilled through the vanes, rather than the cheeks of the plates).

Pad outgassing did not appear to be a significant contributing factor to brake fade, at least not with the pads used for testing, as evidenced by crossdrill holes loosely but completely filled with debris. The authors suggest that, for these pads, the fade mechanism most probably involves the loss of shear strength in the lining surfaces, plastic deformation of asperities in contact, and/or the weakening of the elastic forces that keep pad and rotor asperities in contact. This does not eliminate outgassing as a possible contributing factor to fade in other pads, but testing with a larger cross section of pad materials would be required to determine whether or not interfacial gasses still play a role with certain lining materials.

Brake Wear

For brake system 1, lining wear was comparable between the blanks and crossdrilled rotors at low temperatures, but wear differences increased as temperatures increased up to track temperatures, with the crossdrilled rotors producing much higher pad wear. The authors speculated that, as temperatures increase, even at relatively low braking pressures, the wear rates of pads used with crossdrilled rotors accelerates because of increased extrusion of the pad material into the crossdrilled holes in the rotor plates resulting in an increased mechanical interaction between the linings and the crossdrill hole surface features. This, of course, is also one of the mechanisms by which crossdrilling produces improved braking performance.

The authors predicted a reduction of between 10K and 12K km (between 6200 and 7400 miles), or between 25 and 30% in service life for identical pads used with crossdrilled rotors vs. blanks in brake system 1 used in Los Angeles city traffic. Brake system 2 demonstrated even more accelerated pad wear at the track with crossdrilled rotors compared to blanks, an average increase of 50% in front and 26% out back. These accelerated wear estimates must be weighed against the demonstrated performance benefits of crossdrilling to determine the suitability of upgrading to crossdrilled brakes. At the track, above 600C degrees, the authors noted that lining wear was actually lower with crossdrilled rotors, due to reduced pad glazing resulting in more even pad wear.

The authors observed that introducing crossdrilling to “an otherwise identical rotor design” will reduce its thermal fatigue life. The key phrase here is the one that has been directly quoted. It is common knowledge that the better crossdrilled rotors on the market are not simply drilled blanks, and that adjustments to their design and manufacturing have been made to help offset any increased propensity for cracking.