

Sizing Next Generation High Performance Brake Systems with Copper Free Linings

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ABSTRACT

The high performance brake systems of today are usually in a delicate balance - walking the fine line between being overpowered by some of the most potent powertrains, some of the grippiest tires, and some of the most demanding race tracks that the automotive world has ever seen - and saddling the vehicle with excess kilograms of unsprung mass with oversized brakes, forcing significant compromises in drivability with oversized tires and wheels. Brake system design for high performance vehicles has often relied on a very deep understanding of friction material performance (friction, wear, and compressibility) in race track conditions, with sufficient knowledge to enable this razor's edge design. With significant restrictions in copper content of automotive brake linings becoming reality in California and Washington State in 2021, and a more or less complete phase-out of copper in linings occurring in 2024, one of the key ingredients of high performance linings - critical for heat transfer, high temperature tribofilms, and medium to high temperature friction - can no longer be used.

This paper looks at dynamometer-based performance data from a new generation of copper-free high performance brake linings, and makes comparisons where appropriate to a current copper-containing lining. Following brake system sizing methodologies (some of which have been described in literature previously, and some of which are new and generate improved correlation to race track operation), the brake system of a case study high performance vehicle is reviewed for the impact that the copper free linings has on it. Data are generated using analysis tools, with correlation to vehicle test results. It will be shown that meeting the demands of race track usage with copper-free lining materials is possible, but that it will affect brake system design in some cases.

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INTRODUCTION

The automotive industry is arguably in a "golden age" of vehicle performance. Never before in its history - even considering the fabled "muscle car" era of the 1960's - has such an array of vehicles with true race track performance capability been available basically "turn key" from the factory. Vehicles such as the Corvette Z06, the Camaro ZL1, and the Cadillac CTS-V, sporting 640-650 SAE certified peak horsepower, actually differ little in capability from their race-car siblings (one may observe somewhat cheekily that the only difference is a license plate on the street car versions, and not be far from the truth).

Keeping pace with the capability of the power trains and tires, the brake systems have also evolved. Factory vehicles can be found equipped with some of the largest yet most optimized automotive brake systems in history, cooled by some of the most comprehensive cooling packages (ski ramps, cooling ducts, air deflectors, and other features). Elaborate methodologies have evolved to fit brake systems precisely to

match the capability of race track-bound vehicles and available cooling; parts of some methodologies are published [11-12] and others remain guarded in suppliers and OEM's internal technical memory.

For all of the performance achievements of vehicles today, there are strong challenges already well on their way. The pressures of fuel economy standards that are quickly ramping up around the world, put downward pressures on engine sizing and power, and also have a 'collateral' effect of driving down available airflow for the cooling of powertrains and brakes (due to their impact on aerodynamic drag). Directly in the brake area, and the main subject of this paper, legislation has passed that phases out copper as an "intentional" additive (allowing only trace levels by 2024), thus eliminating a constituent common in performance brake linings with many favorable properties for high temperature use. Advancements in powertrain technology - more and more sophisticated turbo/supercharging, direct injection, variable valve timing, and engine controls, coupled with improving transmission technology, are allowing vehicle performance to remain similar or even improve with

new vehicle generations,, while keeping up with the increasing fuel economy demands (for now, at least). With the changes coming for brakes - in particular the copper-free linings - there is some uncertainty if brake performance can also be retained.

There is a growing body of research [1, 2, 3] describing the effects of the removal of copper on brake lining performance (friction and wear), however, a fairly small subset of these address the topic of performance in race track conditions. The present work will explore the effect of the removal of copper on future high performance vehicle brake system design, first through reviewing performance data (friction and wear) specific to race track conditions, and then applying brake system sizing/modeling methodologies to predict brake system performance on the race track. Comparisons between copper-containing and copper-free brake linings are made wherever possible.

To maximize readability, this paper is organized into the following sections:

1. Friction material impact due to legislation to fade out copper
2. Dynamometer-based Friction/Fade Data
3. Dynamometer-based Wear Data
4. Review of brake system analysis methodology
5. Predicted brake system performance
6. Vehicle Test Results and Correlation
7. Summary/Conclusions

1. FRICTION MATERIAL IMPACT DUE TO LEGISLATION TO PHASE OUT COPPER

Washington State passed the law in 2010 to eliminate copper in brake friction materials in the automotive sector. Chapter 70.285 RCW [13] defines the transition to copper free pads for the automotive sector. The first stage in 2021 will be a reduction of copper content to 5% by weight, and the second stage will be valid in 2025 which forbids the use of copper (allowing trace amounts only, or <0.5% by weight). The new regulation hits the automotive brake sector hard and the suppliers are working diligently to find adequate substitutions for copper in friction materials. Copper has several positive aspects as an important lubricant for brake usage in hot conditions. Copper keeps the wear rate down and protects the rotor to avoid heavy grooving. In addition copper stabilizes the friction output, which leads to an acceptable level brake torque variation.

Rules very similar to RCE 70.285 were adopted by the state of California when Senate bill 346 (which introduced them to California) was signed into law by Governor Schwarzenegger on September 27th, 2010. With this act, a large percentage of the United States automotive market fell under the jurisdiction of these laws. With the significant time and resources it takes to develop and maintain a portfolio of automotive friction materials to meet all of the demanding requirements placed upon them - the automotive friction industry quickly and dramatically shifted its R&D focus to low-

copper and copper-free lining materials (with the majority of efforts bypassing the low copper option, which was a very temporary measure, and going straight to copper free).

2. DYNAMOMETER-BASED FRICTION/FADE DATA

Pad characteristics are mainly measured on inertia dynamometers that are industry standard. The procedures that are used to evaluate brake pads differ strongly amongst engineering organizations. GM developed its own test procedures to cover its needs and to have best image to meet the voice of customer. Two different tests are giving the best overview of the friction material capability in regard to race track driving performance and wear resistance over a specific temperature range.

For this research, we have considered three different high performance friction materials. Material (A) high copper content material as benchmark and two materials (B + C) as zero copper replacements. For the friction comparison, it was used a fade test. The procedure includes a temperature rise of the rotor up to an initial value 800°C (with peak temperatures in excess of 900 °C), initial speeds from 100kph to 250kph and decelerations between 0.6 and 1.2g.

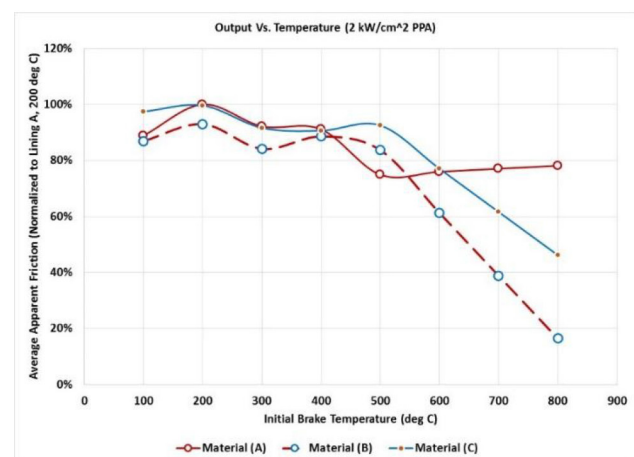
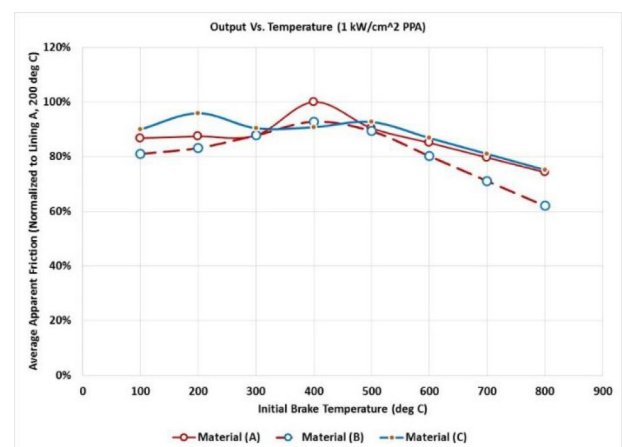


Figure Set 1. Apparent Friction of Copper-containing high performance friction material (A) versus two zero-copper high performance materials (B + C) in inertia-dynamometer based fade mapping test. Data are normalized to the peak value of friction of lining Material (A).

The data are summarized in a 3-dimensional table of apparent friction versus average braking power absorption (normalized by pad area). The pad power absorption metric conveniently embodies both speed and deceleration effects (which are damaging to the friction surface and tend to promote fade at high temperatures) as well as the mitigating effect of spreading out the load over a larger friction surface area. These 3d friction performance maps may then be “sliced” along constant pad power absorption lines corresponding to appropriate braking conditions for various vehicle applications, which results in a friction versus temperature curve appropriate for the speed and deceleration loading condition of the brake.

Figure Set 1 shows data at two Pad Power Absorption (PPA) levels (1.0 and 2.0 kW/cm²) for the three aforementioned friction materials. All data were acquired from inertia dynamometer testing on the same brake corner design and same pad configuration (at the General Motors Milford Proving Grounds brake component development lab).

Material A (used as the reference material for figure set 1) exhibited peak apparent friction at 400 deg C when tested at 1.0 kW/cm² PPA, and peak apparent friction at 200 deg C when tested at 2.0 kW/cm² PPA. With the increase of the initial rotor temperature, the friction coefficient decreases as expected. Compared to the copper free material the output characteristic is changing intensely above 600°C, especially at the higher PPA level. Whereas the new lining generation shows a significant decrease in output, the well-known copper material can maintain the output level up to 800°C. It is especially interesting to note - when contrasting the data at 2.0 kW/cm² PPA in the lower chart of figure set 1 with the data at 1.0 kW/cm² PPA in the upper chart of figure set 1, that the copper-free friction materials also exhibit significantly higher fade sensitivity to the braking power load. Even lining material C, which performed fairly close to the reference material A at the lower PPA level, showed much more degradation than did the reference material A when tested at the higher PPA level. This, in turn, means that certain applications may need larger pad areas to achieve similar performance at the same temperature level when sized with copper-free linings.

3. DYNAMOMETER-BASED WEAR DATA

As already mentioned the copper has a positive impact on hot wear behavior on the friction material side as well on the rotor side. As well, it helps to avoid rotor scoring under track usage where pads and rotor exposed to high temperatures over a long period. Figure 2 shows that the new generation of copper free pads tends to a substantial higher wear rate if the rotor temperature exceeds a threshold. Dramatically increased wear rates can be found when rotor temperature exceeds 600°C.

As a matter of fact the different friction material behavior has a not negligible effect on the brake sizing for the next vehicle generation that have to use a copper free friction material.

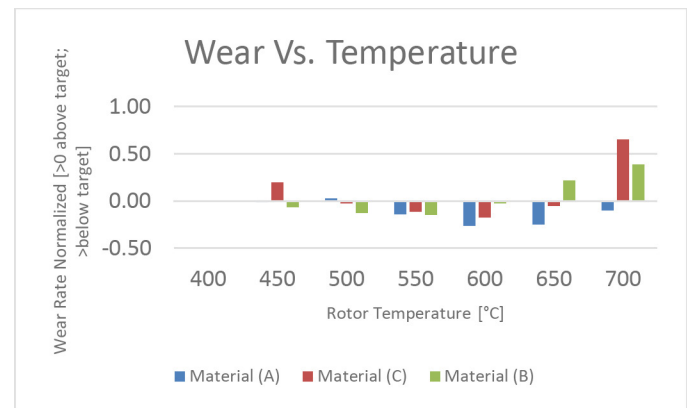


Figure 2. Linear Wear of Copper-containing high performance friction material (A) versus two zero-copper high performance materials (B + C) in inertia-dynamometer based wear test

4. REVIEW OF BRAKE SYSTEM ANALYSIS METHODOLOGY

The mapping of brake corner performance (apparent friction, wear, and fluid consumption behavior) versus operating conditions discussed in the previous sections is part of the foundation for the system level analyses that leads to a workable brake system configuration for race track duty. The brake corners are the parts of the brake system that see the most change in operation conditions between typical road use and race track use, and are arguably the parts for which their performance changes the most in race track conditions. The other “foundations” for good brake system design for the race track have to do with determining what the operating conditions of the brake corners will be on the track. They are, namely, brake cooling, and the brake duty cycle (or usage profile).

The prediction, and optimization of, brake cooling is a very deep topic on its own, and can occupy volumes of literature. Recognizing that the focus of the present paper is copper-free high performance friction materials, the authors will only briefly note some references for interested readers before moving on. The authors will give in to the urge to point out a dated, but highly entertaining (physical test-based) work by Douglas detailing work on NASCAR brake cooling [4]. Significant work on predicting brake cooling using Computational Fluid Dynamics-based methodologies took place starting in earnest in perhaps the mid-1990's to present, and there are a number of fine papers using these methods to optimize components and the surrounding environment of the brake corner [5, 6, 7, 8, 9, 10]. When using measured brake cooling parameters, it is important to note the effect of changing brake rotor material thermal properties, and choose methods of measuring and processing the data that are fitting to the extended temperature range that the rotors see on the race track, as work by Nisonger et al points out [11]. For the present topic covered in this paper, the assumption will be that a credible source of brake cooling data for the application (either measured data on a suitable surrogate vehicle, or high-quality full vehicle CFD simulations) has been made available for the brake system-level analysis.