

Brake System and Subsystem Design Considerations for Race Track and High Energy Usage Based on Fade Limits

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ABSTRACT

The friction material is arguably at the heart of any brake system, with its properties taking one of the most important roles in defining its performance characteristics. High performance applications, such as race track capable brake systems in high powered vehicles, exert considerable stress on the friction materials, in the form of very high heat flux loads, high clamp and brake torque loads, and high operating temperatures. It is important, for high performance applications, to select capable friction materials, and furthermore, it is important to understand fully what operating conditions the friction material will face in the considered application.

Vehicle dynamic effects during testing on the race track and the resultant effect on braking traction available at each wheel can significantly influence the distribution of braking energy within the brake system, often driving individual rotor temperatures significantly higher than most simplified (non vehicle dynamic-dependent) models would predict. Brake force distribution, front vs. rear brake fade behavior, tire traction, and chassis controls behavior can significantly affect the front to rear braking energy distribution. Similarly, differing rotor cooling behavior in effects such as vehicle slip angle and front wheel steer angle will affect the distribution of cooling ability in the vehicle. Within a given brake corner, deflection of the brake caliper, rotor, and pads under braking clamp and torque loads and the resultant changes in pad to rotor pressure distributions can drive a substantial temperature gradient over the surface of the brake rotor. A temperature or heat-flux related issue on any single brake corner can significantly reduce overall brake system performance, in the form of pedal travel increase, fade, thermal roughness, and/or rotor cracking. A successful race-track oriented brake system design accounts for all of these effects and avoids these issues on even the most heavily loaded (from an energy standpoint) brake corner.

This paper first covers a theory of brake fade behavior, which serves to set operating condition limits (a 'fade

envelope') on the brake corners and therefore define the design space for the brake system. It will cover a proposed modeling approach involving brake system and brake corner models utilizing 1-D thermal models. In this approach, a 2-dimensional vehicle dynamics/brake system model is used to predict brake rotor bulk temperatures during race track usage. Next, selected braking events are focused on at the brake corner subsystem level to predict the temperature distribution in the friction interfaces, subject to the operating conditions and design parameters of the brake corner. The results of these analyses are then compared to the fade envelope of the friction material to insure that it is operating below its limits in the intended design. In future work, a full 3-dimensional, lumped parameter vehicle dynamics model will be used to give a more accurate prediction of brake rotor temperatures and temperatures distributions during race track operation.

INTRODUCTION

It is generally well accepted amongst brake system design engineers that race track usage represents one of the most challenging environments for maintaining good brake system performance. The demand for brake systems that are race track capable, yet still meet stringent requirements for NVH, brake lining life, and good pedal feel under typical on-road driving conditions has been more and more prevalent amongst premium brands. Since these applications combine the need for the extreme levels of performance required for race track driving with very high levels of comfort required for high-end luxury vehicles, they represent a very engineering-intensive endeavor for the brake system engineer.

A promising approach to reducing the effort involved in engineering race track capable brake systems to a level that is manageable in typical short vehicle development timeframes is to decouple the development of key components of a system from specific applications. Brake lining materials are one of the most complex engineered composite materials in use today.

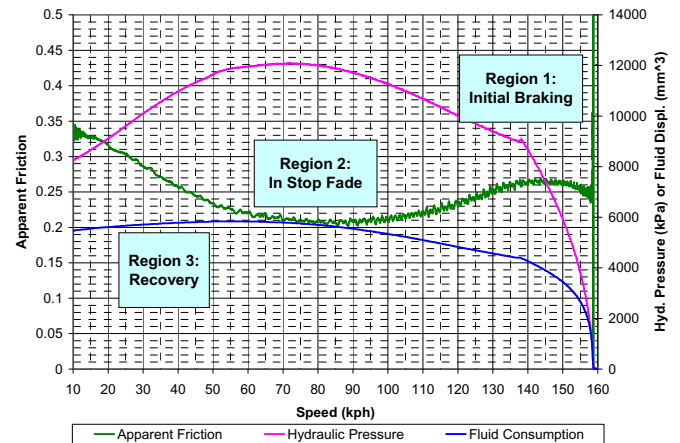
civilization today, and their successful selection involves finding the best balance of performance, comfort, and maintenance for their intended customers. This knowledge is often gained through many years of painstaking testing and field experience. When successful friction materials have been found, there is good reason to keep them in use, and design future brake system applications around their capabilities. This paper will propose a design methodology based on characterizing the operating condition limits of friction materials, in terms of maximum heat flux into the lining friction surface, and maximum brake rotor surface temperatures. The intent is that the brake system designer would start with a friction material or collection of friction materials that have proven success in objective, decoupled testing and in the field for high performance usage, measure the operating limits (referred to as the 'fade envelope' in this paper) of the friction material, and then use these data along with brake system and brake corner modeling, to design brake systems for future high performance applications. The details of this methodology will be developed in the following sections, which will feature examples where possible to illustrate the effects of various brake system and brake corner design parameters:

1. Fade Envelope Theory and Operating Limits
2. General Modeling Approach
3. Effect of System Design Parameters on Bulk Rotor Temperatures (Taguchi DOE)
4. Rotor Surface Temperature and Radial Temperature Distribution
5. Tangential Heat Flux Distribution
6. Case Study
7. Conclusions

1. FADE ENVELOPE THEORY

Examination of in-stop apparent friction behavior of brake corners subjected to high energy braking conditions indicates a similar pattern of behavior in the cases in which brake fade are observed, independent of the friction material on test. Figure 1 below is an example plot of apparent friction versus simulated braking speed on a dynamometer-based fade test, showing in-stop fade. The braking event is divided into three regimes, which will be described in detail below:

Figure 1.1: Apparent Friction vs. Speed with in-stop Fade (constant decel stop, 1.0g target)



Region 1: Initial Braking

In this region, an increase in hydraulic pressure in the caliper overcomes internal force losses and initiates sufficient contact between the pads and rotor to cause an increase in torque output of the brake. The pad and rotor friction surfaces may be very hot at the onset of braking events towards the end of a fade test or race track session, and there will be a temperature field distributed over these surfaces. The shape and composition of the friction surface has generally been changed by the heat exposure and high temperature and by wear mechanisms associated with high temperatures and pressures. The initial, low-pressure 'apparent friction' (note that the term 'apparent friction' refers to the coefficient relating brake torque to the product of hydraulic pressure, piston area, and effective radius of the brake) will often be unstable and difficult to measure, since the high speed, high energy contact over a small area of the friction interface will tend to quickly melt/fracture the asperities participating in the friction process, and rotor LRO and TV will result in significant variation in the pad to rotor interfacial pressure. As pressure is increased to the point of engaging enough of the friction interface to withstand the heat input without immediately failing, and to where interfacial pressure is significant relative to the variation imparted by LRO and DTV, a stable (e.g. measurable) apparent friction level forms. In an in-stop fade condition, this regime lasts only momentarily (it is generally over before the full target deceleration level has been reached).

Region 2: In-Stop Fade

When deceleration is fully developed and the brake is still at high speed, significant heat is generated at the friction interface. Compression pressure from the caliper and conforming wear lining at the points of highest contact pressure brings more and more of the friction interface into significant contact. In most cases significant gradients in the pad to rotor interfacial pressure distribution persist, due to taper wear imparted by previous events and distortion of the caliper housing under pressure and braking torque stresses. The regions of the friction interface that receive the highest

balance of heat flux in from braking friction versus heat flux out from conduction will overheat first, melting and/or chemically decomposing the least temperature-resistant components of the lining material (often the phenolic resin binder, when applicable), and in some extreme cases melting the surface of the brake rotor. The decomposition and weakening of the friction material surfaces reduce the interference between the pad and rotor asperities, as heat affected asperities become more easily deformed, more easily moved within their constraints in the lining matrix, and more easily dislodged completely. These regions of the brake lining enter a rapid wear state. The rapid wear of the pad will quickly and significantly change the contact pressure distribution, and therefore the heat flux distribution. It also removes a significant amount of heat from the friction interface, in the form of the wear mechanisms absorbing heat energy, and then the high temperature wear particles exiting the friction interface (rotor wear particles are often seen as a shower of sparks during braking). If the braking energy is low enough, the involvement of lower temperature, more resilient regions of the friction interface, and the removal of heat from the interface in the rapid wear regions will stabilize the overall apparent friction of the brake, thus limiting the amount of in-stop fade. If enough braking energy is present, then the regions of the friction interface that are overheated will spread until much of the friction surface is overheated. When this occurs, the subsystem-level symptom is significant in-stop fade. Since in-stop fade involves significant wear of the lining and in many cases (for performance-oriented linings) the rotor, a significant quantity of wear debris flows through the friction interfaces. This will give rise to a potentially highly dynamic third body (transfer film), which, until stabilized with the right conditions in the friction interface, can also interfere with the normal frictional mechanisms in the interface and contribute to fade.

Many lining materials are especially susceptible to in-stop fade when in a green or relatively green condition. This is due a number of effects, including the friction surfaces being geometrically incompatible with one another for high energy braking conditions with very high localized contact pressure and heat flux in small regions of the friction interface. It may be due in small part, with some friction materials, to 'outgassing' – the buildup of gas pressure in the friction interface from heat-triggered chemical reactions in the friction material – but GM internal studies measuring outgassing pressure have shown it to have minimal effect on apparent friction on the lining materials studied. It is also due to the absence of a history of wear debris flow through the interface at elevated temperatures, which when compacted by braking pressures and temperatures (along with various chemical reactions between the pad and rotor materials, and these materials and their environment) form a transfer film on the rotor and pad surfaces compatible with higher energy usage. The formation of a stable higher temperature transfer film changes the micromechanical interaction between the linings and

rotor from one of harsh contact between fewer, but sharper and longer asperities (which can lead to asperity destruction, high wear, and fade) to one of softer contact between more numerous, compatibly-worn asperities. The higher quality asperity contact after the formation of a stable high temperature transfer film is encouraged by the material in the transfer film limiting individual asperity interaction but distributing interactions to more asperities, and by the linings and rotor being worn into a more globally compatible shape (which results in more even contact pressure). It is known the high temperature exposure chemically changes the lining friction surface as well, but the resultant friction surface properties are not well understood and little information is available in literature. It is expected that for race track usage, the friction materials would have been burnished with sufficient energy to establish a compatible wear pattern and stable high temperature transfer film.

Region 3: Recovery

Study of numerous braking events for which significant fade has occurred has revealed that recovery – a significant increase in apparent friction towards the end of a braking event - almost always occurs if the braking event is maintained long enough, regardless of the severity of fade. As a braking event for which fade has occurred progresses and the sliding speed of the brake is reduced, the energy input into the friction interface also becomes lower as well. As noted in the discussion of in-stop fade above, an 'equilibrium' of sorts is reached in which rapid wear in the most heat affected regions of the friction interface and exposure of more resilient material underneath, the removal of heat from the interface via this rapid wear, and the re-distribution of braking energy throughout the interface due to wear become sufficient to support the braking load. Recovery is gradual at first and may still be accompanied by significant lining and rotor wear, but often sets in very aggressively towards the end of the stop.

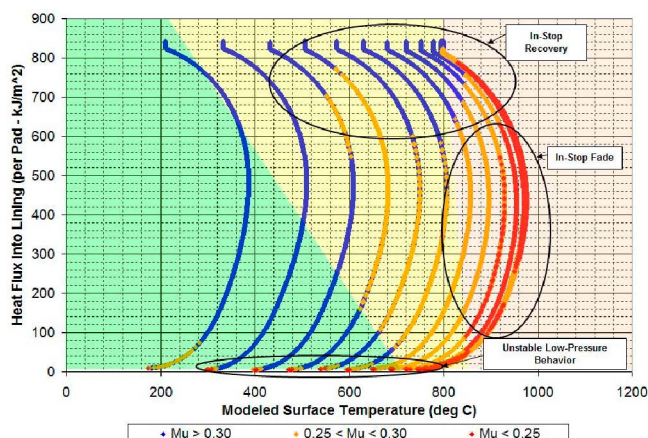
Additional friction mechanisms can become more significant as the sliding speeds become low. Time dependent, viscoelastic deformation of asperities of the brake pad into higher-quality contact with rotor asperities can increase apparent friction at lower sliding speeds. In addition, lowering of the braking energy to a point that no longer supports rapid wear of the friction surfaces will decrease the flow of wear debris through the interface and allow the transfer film to stabilize. A stable transfer film will cause less interference in pad to rotor micromechanical interactions, and can even participate in the friction process itself.

Analysis of the above-described general mechanism of brake fade leads immediately to a brake system design space – an 'envelope' of operating conditions, predicated on the notion that severe in-stop fade is to be avoided – that is specific to a given choice of friction material. This design space is defined by the following concepts:

- The brake friction interface temperature at the initiation of any braking event must be low enough to avoid large-scale overheating of the friction interface. This is accomplished through sizing, thermal properties, and cooling of the brake rotors
- The brake pad area must present enough material at the friction interface to avoid wide-scale overheating – in other words, it must have enough area so that progression of overheating of the friction interface will require more single-stop energy than is anticipated for the intended application. This is accomplished through pad and rotor friction surface sizing.
- When the above conditions cannot be practically met for a given application, then the constraints on the system design and the expected energy loading of the brake system will drive friction material choice.

The design space for a subject brake lining material may be found from any set of test data that results in sufficient stress for the friction material (e.g. severe fade), but that is progressive enough to allow the limits to be discovered with sufficient accuracy. Friction data from multiple braking events may be plotted versus modeled rotor surface temperature and heat flux into the pads. In the example plot below, friction data from a 20-stop, 160 kph to 0, 1.0g decel fade test were separated into three major categories – severe fade ($\mu < 0.25$, moderate fade ($0.25 < \mu < 0.30$) and no fade to in-stop friction increase ($\mu > 0.30$). Rotor surface temperatures were computed using the 1-dimensional thermal model proposed by Sheridan and Kutchey [2] – this, and an adaptation of it to predict radial temperature distribution for a given pressure field will be discussed in more detail in section 4. The thresholds for each major category were plotted, and a line fitted to each boundary. Note the appearance of curved lines in this plot and in the plot of figure 1.3 – points along one of these curved lines represent data associated with a single braking event:

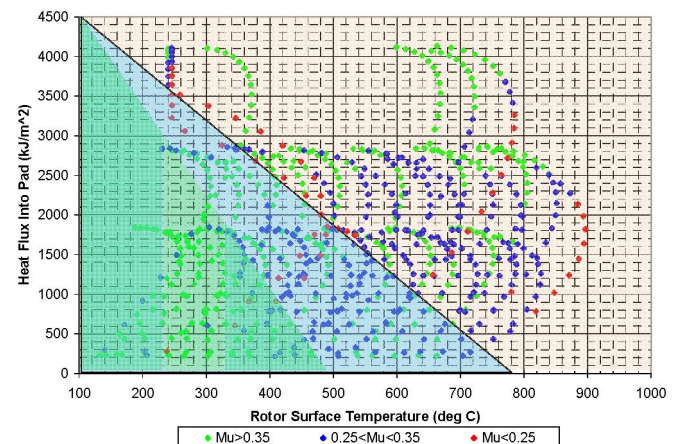
Figure 1.2: Example Fade Envelope Data (European Low-Metallic Lining)



An inertia dyno-based test procedure is under development that will subject friction materials to progressively higher energy loading and initial brake temperatures, with the intention of gradually overstressing the friction materials and finding more precisely where the operating limits lie. It should be noted that the brake caliper performance (pressure distribution characteristics and mechanical efficiency) can affect the results, so the friction material should be evaluated in a known 'good' high performance caliper design (a caliper design that includes features for controlling radial and tangential taper wear, and packages sufficient lining area and volume for HP use).

Figure 1.3 shows data generated from this procedure on a race-track capable lining material. Note that there is some overlap in apparent friction behavior for different combinations of rotor surface temperature and heat flux into the pad; this is due in general to the conditioning effect of prior braking events on the lining friction surface and due to green fade in an early braking event. The fade envelope limit was purposely placed so as to exclude data from green fade. It was also represented as a straight line; this was for graphical simplicity (the actual relationship is non-linear, as indicated by the significance of non linear terms in the regression model of figure 1.4). The procedure for placing the fade envelope lines in figures 1.2 and 1.3 was somewhat subjective. The ultimate intent is to use a considerably more accurate model for the friction data (such as a neural network model) to represent it for design purposes; the graphical plot is a highly simplified representation of the data:

Figure 1.3: Fade Envelope generated by Fade Envelope Inertia Dyno Procedure with Race-Track Capable Lining Material



Analysis of Variance results for some of the factors considered to be predictors for apparent friction behavior appear below; the fact that all of the selected factors (rotor surface temperature, heat flux into the pad, prior temperature and peak braking power in the form of deceleration multiplied by initial speed) and/or their squares test as significant with p-values $\ll 0.05$ confirms their strong relationship to apparent friction.

The overall regression model correlation coefficient is relatively low ($R^2 = 43.8\%$) but the p-value is also very low ($p < 0.0005$) which indicates the relationships between apparent friction and the selected factors is significant but not complete. As noted previously, the intent would be to use a more accurate (likely neural network-based) model to represent the fade envelope data for actual design work. Preliminary efforts (not to be covered in this paper) show correlation coefficients above 90% with neural network models. In figure 1.4 below, the terms are as follows:

- VinitXDecel is the interaction term for initial speed and target constant deceleration of the event
- Tsurf is the modeled rotor surface temperature (see section 4 for more detail)
- Tsurf^2 is the square of the above term
- Flux is the heat flux into the pad
- Flux^2 is the square of the above term
- Prior T is the peak modeled rotor surface temperature of the prior braking event in the test

Figure 1.4: Apparent Friction Analysis of Variance Results

The regression equation is

$$\mu = 0.448 - 0.000767 \text{ VinitXDecel} - 0.000130 \text{ Tsurf} + 0.000000 \text{ Tsurf}^2 - 0.000022 \text{ Flux} + 0.000000 \text{ Flux}^2 + 0.000033 \text{ Prior T}$$

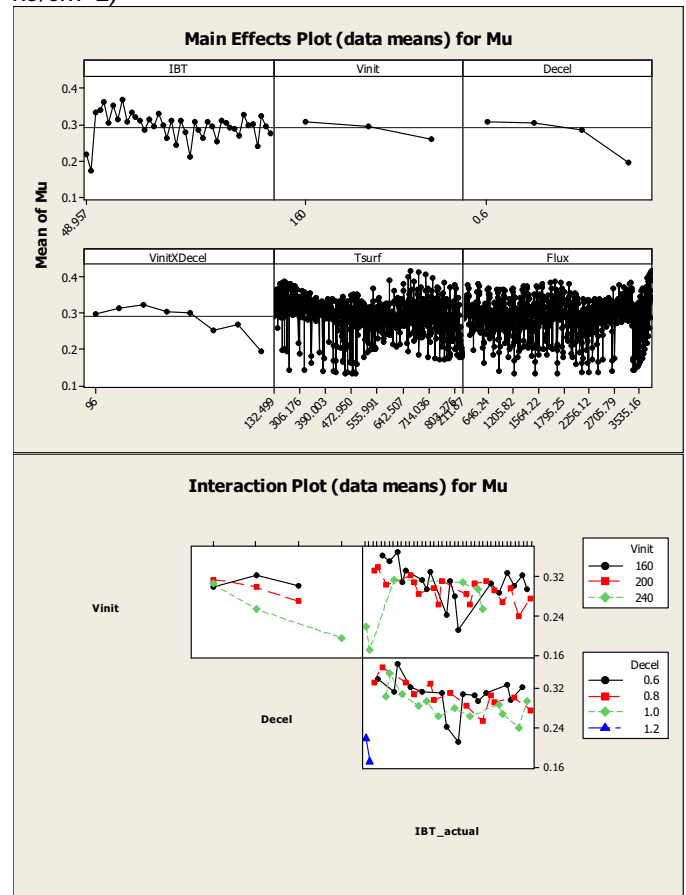
Predictor	Coef	SE Coef	T	P
Constant	0.44784	0.01536	29.15	0.000
VinitXDecel	-0.00076674	0.00003432	-22.34	0.000
Tsurf	-0.00012997	0.00005173	-2.51	0.012
Tsurf^2	0.00000005	0.00000005	1.00	0.318
Flux	-0.00002219	0.00000554	-4.00	0.000
Flux^2	0.00000001	0.00000000	6.75	0.000
Prior T	0.00003258	0.00000913	3.57	0.000

S = 0.0393441 R-Sq = 44.3% R-Sq(adj) = 43.8%

Source	DF	SS	MS	F	P
Regression	6	0.91372	0.15229	98.38	0.000
Residual Error	743	1.15013	0.00155		
Total	749	2.06385			

The main effects plots in figure 1.5 show the relationship between energy into the brake (decel and speed), peak power into the brake (decel x initial speed), and apparent friction quite clearly, with apparent friction increasing to an optimal energy input and then decreasing with increasingly severe fade with higher and higher energy loading. A slight trend is visible in the initial brake temperature, rotor surface temperature, and heat flux into the pad plots, but it is not as visible due to the large number of data points and the strong interactions between energy input and temperatures in predicting apparent friction. The interactions plot in figure 1.5 confirms some of these interactions quite clearly, especially the initial speed and target deceleration interaction:

Figure 1.5: Selected Main Effects and Interactions Plots for Apparent Friction Behavior (IBT = initial braking temperature in deg C, Vinit = initial braking speed in kph, Decel = target constant deceleration for braking event in g, Vinit X Decel = initial speed and target deceleration interaction term, Tsurf = modeled rotor surface temperature in deg C, Flux = heat flux into brake pad in kJ/cm^2)



2. GENERAL MODELING APPROACH

An approach to brake system design for high-performance usage, based on the measured 'fade envelope' of a selection of friction materials, is described in this section.

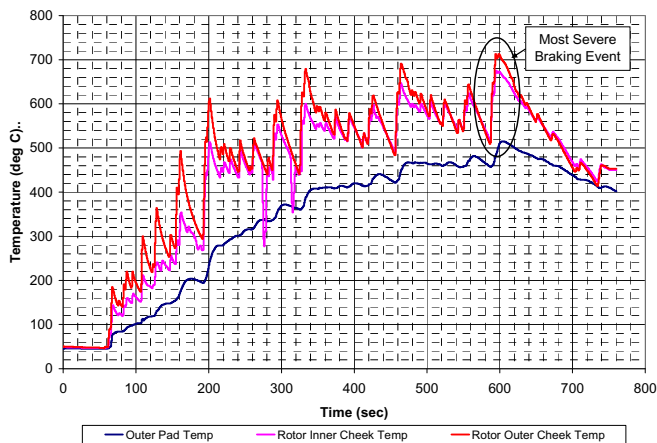
The process begins by measuring the fade envelope of suitable friction materials. This can be done in a manner that is decoupled from any specific vehicle application; the object is to build up a 'library' of high performance friction material fade envelopes for future use. Due to the fact that (as described in section 1), the fade behavior of a given friction material is somewhat dependent on the heat flux distribution and pressure distribution within the friction interface, it is important for friction materials to be evaluated on proven high performance brake corner designs.

Next, the brake usage conditions (test or race track schedule, such as the high speed Auto Motor Und Sport brake test or the General Motors Milford Road Course) that will be used to drive the brake system design

specified. These test conditions should be representative of the most extreme braking conditions that the vehicle will be subjected to. Multiple conditions may be considered.

When the brake usage conditions are fully specified, then the brake rotor bulk temperature profiles for each condition under consideration are generated by thermal analysis (analytical approach) or by adjusting previously measured data from a similar vehicle to the specifications of the new vehicle application (empirical approach). An example temperature trace appears in the figure below, showing rotor and corresponding brake pad temperatures for the most heavily loaded brake corner (the left front, from a generally clockwise-running track):

Figure 2.1: Example Bulk Temperature Trace from Race Track Testing



As may be seen in the example data, brake rotor temperatures increase to a pseudo-equilibrium level, with temperature fluctuations driven by braking and cooling intervals. The most extreme braking events – the events with the most significant change in bulk temperature, and the events with the highest peak temperatures, are the ones most at risk for producing significant fade. These events generally correspond to the braking events after long straight sections on the race track, and braking events in rapid succession. They are flagged for more detailed analysis. In the case of this example, there is a single braking event per lap that produced both the highest peak temperatures, and the highest single stop temperature rise; this clearly identifies it as the most severe. It is worth noting in the example data that the rotor temperature reading is significantly more responsive, and of higher magnitude than the pad temperature reading. The highest energy braking events are clearly visible in the rotor temperature data, but barely visible in the pad temperature trace.

Once a single braking event or a collection of braking events have been flagged for producing the highest energy input and/or the highest brake rotor bulk temperatures, a more detailed, subsystem-level model

may be used to predict heat flux into the brake pads, and the brake rotor surface temperature / surface temperature distribution for each of these events. The object of these analyses is to insure that the brake rotor surface temperatures and heat flux into the friction interfaces do not exceed the operating limits defined by the fade envelope of the friction material. A conservative design approach is to insure that no region of the friction interface in the brake design being evaluated exceeds these limits – conservative, because the brake corner on which the fade envelope was evaluated will have some level of surface temperature gradient which affects its fade behavior, which is neglected by applying this rule.

If the fade envelope of the friction material selected for the vehicle application under consideration is exceeded by the operating conditions imposed by the vehicle, then this information may be used to drive one or more of the following major categories of design changes:

1. Improve brake cooling to lower temperatures – generally accomplished through brake rotor design, cooling ducts and underbody airflow features (including channels, deflectors, brake to wheel placement, airdams, etc), and wheel design. In some cases rotor crossdrilling can improve cooling, but at the expense of lining wear rates [1].
2. Reduce energy input to heavily loaded brakes to lower temperatures – generally accomplished through adjusting brake balance and chassis controls tuning
3. Reduce the heat flux into the friction interface – accomplished through adjusting pad and rotor sizing. In cases where the violation of the friction material fade envelope is localized due to heat flux distribution issues in the caliper, this may involve design changes to the caliper to correct these issues.
4. Selecting a friction material with a larger fade envelope – this choice will inevitably invoke a set of performance tradeoffs associated with more fade resistant friction materials. In some cases rotor friction surface features such as crossdrilling, slotting, or both can extend the fade envelope of a compatible friction material, at the expense of lining wear rates.

3. EFFECTS OF BRAKE SYSTEM DESIGN PARAMETERS ON BULK ROTOR TEMPERATURES

In order to more fully understand the effects of vehicle and brake system design parameters on brake rotor bulk temperature during race track events, a simple analytical experiment was conducted. The experiment consisted of a simulation of a high performance vehicle driving six laps of the General Motors Milford Road Course while twelve design parameters were varied and brake rotor temperatures were reported for analysis.