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White Paper:

Brake Systems and Upgrade Selections

While almost every current passenger car is capable of a single stop from maximum speed at or near the limit of tire adhesion, the braking systems of most passenger vehicles and light trucks and some sports cars are not adequate for hard or sport driving or for towing. Most stock brake systems lack sufficient thermal capacity - the system's ability to absorb and transfer heat by conduction, convection and radiation into the air or surrounding structure during severe driving.

In addition, many stock calipers and their mountings are structurally not stiff enough at higher line pressures and the resultant higher clamping loads. That is why even though there is enough front brake torque to lock the front wheels at highway legal speeds, caliper flex at the increased system pressure required to stop the car from high speed may prevent wheel lock up. Needless to say, most OEM brake pads are also not designed for severe use, since cold stopping performance and quiet operation typically are considered more important to new car buyers.

Several factors should be considered in the selection of high performance aftermarket braking systems. Some have to do with performance and safety, some with ease of installation and some with cost. The object is to select the system that will reliably fulfill your long-term needs with the least trouble and the least cost.

There are a few basic facts that must always be kept in mind when discussing brake systems:
1) The brakes don't stop the vehicle - the tires do. The brakes slow the rotation of the wheels and tires. This means that braking distance measured on a single stop from a highway legal speed or higher is almost totally dependent upon the stopping ability of the tires in use - which, in the case of aftermarket advertising, may or may not be the ones originally fitted to the car by the OE manufacturer.

2) The brakes function by converting the kinetic energy of the car into thermal energy during deceleration - producing heat, lots of heat - which must then be transferred into the surroundings and into the air stream. The amount of heat produced in context with a brake system needs to be considered with reference to time meaning rate of work done or power. Looking at only one side of a front brake assembly, the rate of work done by stopping a 3500-pound car traveling at 100 Mph in eight seconds is 30,600 calories/sec or 437,100 BTU/hr or is equivalent to 128 kW or 172 Hp. The disc dissipates approximately 80% of this energy.
The ratio of heat transfer among the three mechanisms is dependent on the operating temperature of the system. The primary difference being the increasing contribution of radiation as the temperature of the disc rises. The contribution of the conductive mechanism is also dependent on the mass of the disc and the attachment designs, with discs used for racecars being typically lower in mass and fixed by mechanisms that are restrictive to conduction. At 1000 degrees F. the ratios on a racing 2-piece annular disc design are 10% conductive, 45% convective, 45% radiation. Similarly on a high performance street one-piece design, the ratios are 25% conductive, 25% convective, 50% radiation.

3) Repeated hard stops require both effective heat transfer and adequate thermal storage capacity within the disc. The more disc surface area per unit mass and the greater and more efficient the mass flow of air over and through the disc, the faster the heat will be dissipated and the more efficient the entire system will be. At the same time, the brake discs must have enough thermal storage capacity to prevent distortion and/or cracking from thermal stress until the heat can be dissipated. This is not particularly important in a single stop but it is crucial in the case of repeated stops from high speed - whether racing, touring or towing.

4) Control and balance are at least as important as ultimate stopping power. The objective of the braking system is to utilize the tractive capacity of all of the tires to the maximum practical extent without locking a tire. In order to achieve this, the braking force between the front and rear tires must be nearly optimally proportioned even with ABS equipped vehicles. At the same time, the required pedal pressure, pedal travel and pedal firmness must allow efficient modulation by the driver.

5) Braking performance is about more than just brakes. In order for even the best braking systems to function effectively, tires, suspension and driving techniques must be optimized. For maximum brake potential, vehicles benefit from proper corner weight balance, a lower CG, a longer wheelbase, more rear weight bias and increased aerodynamic downforce at the rear.

To go further it is necessary to understand some of the physics involved, and that requires some definitions:
1) Mechanical pedal ratio: Because no one can push directly on the brake master cylinder(s) hard enough to stop the car, the brake pedal is designed to multiply the driver's effort. The mechanical pedal ratio is the distance from the pedal pivot point to the effective center of the footpad divided by the distance from the pivot point to the master cylinder push rod. Typical ratios range from 4:1 to 9:1. The larger the ratio, the greater the force multiplication (and the longer the pedal travel).

2) Brake line pressure: Brake line pressure is the hydraulic force that actuates the braking system when the pedal is pushed. Measured in English units as pounds per square inch (psi), it is the force applied to the brake pedal in pounds multiplied by the pedal ratio divided by the area of the master cylinder in square inches. For the same amount of force, the smaller the master cylinder, the greater the brake line pressure. Typical brake line pressures during a stop range from less than 800psi under "normal" conditions, to as much as 2000psi in a maximum effort.

3) Clamping force: The clamping force of a caliper is the force exerted on the disc by the caliper pistons. Measured in pounds clamping force, it is the product of brake line pressure, in psi, multiplied by the total piston area of the caliper in square inches. This is true whether the caliper is of fixed or floating design. Increasing the pad area will not increase the clamping force.

4) Braking torque: When we are talking about results in the braking department we are actually talking about braking torque - not line pressure, not clamping force and certainly not fluid displacement or fluid displacement ratio. Braking torque in pounds-feet on a single wheel is the effective disc radius in inches times clamping force times the coefficient of friction of the pad against the disc all divided by 12. The maximum braking torque on a single front wheel normally exceeds the entire torque output of a typical engine.

A few things are now obvious:
1) Line pressure can only be increased by either increasing the mechanical pedal ratio or by decreasing the master cylinder diameter. In either case the pedal travel will be increased.

2) Clamping force can only be increased either by increasing the line pressure or by increasing the diameter of the caliper piston(s). Increasing the size of the pads will not increase clamping force. Any increase in caliper piston area alone will be accompanied by an increase in pedal travel. The effectiveness of a caliper is also affected by the stiffness of the caliper body and its mountings. It is therefore possible to reduce piston size while increasing caliper stiffness and realize a net increase in clamping force applied. This would typically improve pedal feel.

3) Only increasing the effective radius of the disc, the caliper piston area, the line pressure, or the coefficient of friction can increase brake torque. Increasing the pad area will decrease pad wear and improve the fade characteristics of the pads but it will not increase the brake torque.

FRONT TO REAR BRAKE BIAS
Stability and control under heavy braking is at least as important as ultimate stopping capability. All cars, from pickups to Formula One, are designed with the majority of the braking torque on the front wheels. There are two reasons for this - first, if we ignore the effects of aerodynamic downforce, the total of the forces on each of the vehicle's four tires must remain the same under all conditions. When the vehicle decelerates, mass or load is transferred from the rear tires to the fronts. The amount of load transfer is determined by the height of the vehicle's center of gravity, the length of the wheelbase and the rate of deceleration. Anti-dive geometry does not materially affect the amount of load transferred - only the geometric results of the transfer.

Second, when a tire locks under braking, braking capacity is greatly reduced but lateral capacity virtually disappears. Therefore, when the front tires lock before the rears, steering control is lost and the car continues straight ahead - but this "understeer" is a stable condition and steering control can be regained by reducing the pedal pressure. If, however, the rear tires lock first, the result is instantaneous "oversteer" - the car wants to spin. This is an unstable condition from which it is more difficult to recover, especially when entering a corner.

Most mid-engine pure racing cars are designed with 55-60% of the total static load and 45-50% of the total braking torque on the rear tires. These cars feature literally tons of rear aerodynamic downforce and the footprints of the rear tires are always significantly larger than those of the front. Most passenger cars are front engined; none of them have any appreciable downforce and almost all of them have the same size front and rear tires. In extreme cases (front wheel drive) they may have 70% of the total static load on the front tires. They are therefore designed with a preponderance of front brake torque.

Most current production cars feature anti-lock brake systems (all cars should). Sophisticated ABS systems ensure that, under heavy braking conditions - even braking with tires on different surfaces - each tire is braking at something very closely approaching its maximum capacity while the ABS system prevents lockup.

THE REAR BRAKE LINE PRESSURE-LIMITING VALVE
Since the load transferred from the rear tires to the fronts under braking decreases the braking capacity of the rear tires, a rear brake line pressure-limiting valve (often referred to as a proportioning valve) is utilized to prevent rear wheel lock up on most passenger cars that do not feature ABS. Its function is to limit the amount of pressure transmitted to the rear brakes under very heavy braking. Assuming a tandem master cylinder with equal bores, front and rear line pressures are the same until some pre-determined threshold is reached. After this point, rear line pressure, while it still increases linearly with pedal effort, increases at a lower rate than the

front. In a graph it appears as a distinct "knee" point where a further rise in pressure after the valve is noticeably diminished. The purpose is to avoid rear wheel lockup and the attendant unstable oversteer at maximum deceleration rates when the weight transfer is greatly reducing the dynamic load on the rear wheels.

It is not a good idea to remove the limiting valve from a road going automobile. Remember, understeer is stable, oversteer is not. Without an effective anti-lock braking system, in any panic braking situation we must be absolutely certain that the unloaded rear tires cannot lock first. Therefore materially increasing the rear braking torque is not a good idea for highway use. If you feel that you must do so, consider removing the OEM rear brake line pressure-limiting valve completely and replace it with an adjustable unit. Do not place a second pressure-limiting valve in line with the OEM unit.

BRAKE PEDAL FIRMNESS AND MODULATION
The human brain/body system modulates most effectively by force, not by displacement. The side control sticks on current fighter aircraft hardly move. The feel of the brake pedal should approach the firmness and consistency of a brick. There are several factors at work here:

1) Brake hoses: Optimum pedal firmness cannot be achieved with the stock fabric reinforced rubber flexible hoses which swell under pressure - decreasing pedal firmness while increasing both pedal travel and brake system reaction time. The first step in upgrading the braking system of any vehicle is to replace the OEM flexible hoses with stainless steel braid protected flexible hoses of extruded Teflon. Make certain that they are designed for the specific application, are a direct replacement for stock and are certified by the manufacturer to meet USDOT specifications. A claim that aftermarket hoses are certified by the DOT is a caution flag. The DOT does not certify anything. Manufacturers certify that their products meet DOT specifications and legitimate suppliers can produce reports from DOT approved testing laboratories. When upgrading your brake hoses, replace both the front and rear hoses. Due to their swelling under pressure the stock hoses take a measurable amount of time to transmit pressure to the calipers. Replacing the front hoses only will result in a built in lag time to the rear brakes and may also adversely effect the microprocessor control algorithms of the ABS system.

2) Master cylinders and caliper piston diameters: While it is true that the most effective master cylinder arrangement is the twin cylinder with adjustable bias bar that is universal in racing, replacing the OEM master cylinder on a road going car is simply not practical. When selecting an aftermarket system, make sure that the caliper bores are designed for the specific application.

3) Disc run-out and thickness variation: Run-out in excess of six thousandths of an inch (0.006") can be felt by the driver as can more than 0.001" of thickness variation and any amount of material transfer from overheated pads. Run-out is caused by poor design of either the cooling vanes or the junction between the friction surfaces and the mounting bell, by poor machining, by thermal stress or by any combination of the three.

4) Caliper and caliper mounting stiffness: Clamping force tries to open the opposing sides of the calipers - resulting in a longer than optimum pedal travel and uneven pad wear. The only solution is optimal mechanical design and material selection - there is no effective development fix for "soft" calipers. Also, the stiffest caliper will be ineffective if its mounting lacks rigidity.

5) Out of balance discs (or tires): The driver cannot modulate the brake on a bouncing wheel. Compared to tires, disc diameters are relatively small, but all discs should be balanced. As the installation of balancing clips will interfere with airflow the preferred method is to remove material from the heavy side. Significant core shift in the casting (visible, as thickness variation on individual friction surfaces will result in incurable dynamic imbalance.

6) Pad "bite" and release characteristics: For efficient modulation the pads must "bite" immediately on brake application and must release immediately when the pedal is released. This is purely a matter of pad selection. It is seldom a good idea to use different compound pads front and rear and never a good idea to use a pad with more bite or a higher coefficient of friction at the rear.

BRAKE FADE
Repeated heavy use of the brakes may lead to "brake fade." There are two distinct varieties of brake fade:

1) Pad fade: When the temperature at the interface between the pad and the disc exceeds the thermal capacity of the pad, the pad loses friction capability due partly to out-gassing of the binding agents in the pad compound. Pad fade is also due to one of the mechanisms of energy conversion that takes place in the pad. In most cases it involves the instantaneous solidification of the pad and disc materials together - followed immediately by the breaking of bonds that releases energy in the form of heat. This cycle has a relatively wide operating temperature range. If the operating temperature exceeds this range, the mechanism begins to fail. The brake pedal remains firm and solid but the car won't stop. The first indication is a distinctive and unpleasant smell that should serve as a warning to back off.

2) Fluid boiling: When the fluid boils in the calipers, gas bubbles are formed. Since gasses are compressible, the brake pedal becomes soft and "mushy" and pedal travel increases. You can probably still stop the car by pumping the pedal but efficient modulation is gone. This is a gradual process with lots of warning.

In either case temporary relief can be achieved by heeding the warning signs and letting things cool down by not using the brakes so hard. In fact, a desirable feature of a good pad material formula is fast fade recovery. Overheated fluid should be replaced at the first opportunity. Pads that have faded severely should be checked to make sure that they have not glazed and the discs should be checked for material transfer. The easy permanent cures, in order of cost, are to upgrade the brake fluid, to upgrade the pads, or to increase airflow to the system (including the calipers). In marginal cases one of these or some combination is often all that is required.

TAPERED PAD WEAR
Similar to brake fade, there is more than one distinct type of tapered pad wear - radial taper and longitudinal taper.

1) If a caliper lacks stiffness and tends to "open" under clamping force, at elevated temperatures, the outboard surface (edge with the longest radius) of the pad with respect to the disc (axle), center will wear faster than the inboard (edge with the shortest radius), and the pad will be tapered in its cross section when viewed from the end. This is termed "radial taper."

2) The trailing area (portion) of the pad, to some extent "floats" on the entrapped gasses and particulate matter generated from the leading portion of the pad. The leading portion of the pad will always be hotter than the trailing portion and so will correspondingly wear faster - resulting in a pad that is tapered when viewed from the edge. This phenomenon is termed "longitudinal taper."

The differential in heat generated across the pad surface, leading to trailing, is characteristic regardless of caliper and pad design. This is why all racing calipers and most high performance street calipers have differential piston bores. Most high performance pads also feature a tapered leading edge.

3) In the case of new very thick pads like the type used for endurance racecars, longitudinal taper will sometimes occur because the pad literally tips inward at an angle against the disc during "off brake" conditions. When this happens, there is a small amount of force pushing the pad leading edge in the direction of the disc as a result of the contact and the friction generated. At the same time, the trailing side of the pad is wedged back into the corner of the pad cavity in the caliper and against the abutment plate, which further promotes contact at the leading edge. This situation is exaggerated with new thick pads since the increased offset of the pad friction surface from the backing plate, results in a relatively larger constant force vector in the direction of the disc.

4) Taper can also be seen where the disc is solidly fixed to the hat or where the hat and disc are one piece. In either case, the taper created will appear as more wear on the outer diameter of the outside pad, and the inner diameter of the inside pad. This is due to operating the brakes at high temperature and the resulting thermal expansion forces on the annular outer ring structure of the disc called the friction plates. The center of the disc or hat limits the expansion of the outer structure on only one side where it is joined, typically at the outside friction plate. As a result, the disc “cones” so that it is concave as viewed from the outside (See also "Floating Discs"). Subsequently due to the coning, the pad contacts unevenly when the brakes are applied or remains in contact with the disc in the regions mentioned and even higher temperatures and wear are the result.

AIR COOLING
Most of the enormous amounts of heat generated during deceleration must be dissipated into the free air stream.

Most high performance (and/or heavy) cars today use some variation of the "ventilated" brake disc in which air entering the center or "eye" of the rotor is forced through the interior of the rotor by the pumping action of the rotating assembly. The most efficient practical way yet devised to accomplish this is through the use of the "curved vane" ventilated brake rotor originally designed for the LeMans winning Ford GT 40s in 1966. In this design the interior vanes are curved to form an efficient pump impeller. They also stabilize the rotor from distortion and serve as very effective barriers to stop the propagation of cracks due to thermal stress.

In laboratory testing STOPTECH's patented design developments in the 48 vane rotors have increased air flow through the rotor by an astounding 61% over some OEM rotors and from 10-15% over racing rotors of the same size. This results in a cost-effective but very stable direct replacement rotor that runs typically 15% cooler than stock and 7% cooler than racing designs.

TITANIUM CALIPER PISTONS
Caliper pistons manufactured from Titanium do a really good job of insulating the fluid in the caliper from conductive heat transfer from the pads. Unfortunately it is not a simple substitution. The design and manufacture of brake caliper pistons is a complex engineering exercise. If the piston material is to be changed,

the designer must take into consideration the difference in thermal coefficient of expansion between the OEM material and the new material. The right grade and condition of Titanium must be selected. The surface finish and treatment must be compatible with the seals. If the seal groove is in the piston, the groove geometry must match the OEM design.

As a point of interest, virtually all serious racing cars use Titanium caliper pistons with an anti-galling surface treatment, which changes the color from a natural dull silver to gold. The fact of the matter is that a simple Titanium button placed inside the OEM piston does about 70% of the job at a fraction of the cost with no risk of damaging anything by disassembling the caliper.

DRILLED VS. SLOTTED ROTORS
For many years most racing rotors were drilled. There were two reasons - the holes gave the "fireband" boundary layer of gasses and particulate matter someplace to go and the edges of the holes gave the pad a better "bite."

Unfortunately the drilled holes also reduced the thermal capacity of the discs and served as very effective "stress raisers" significantly decreasing disc life. Improvements in friction materials have pretty much made the drilled rotor a thing of the past in racing. Most racing rotors currently feature a series of tangential slots or channels that serve the same purpose without the attendant disadvantages.

PAD AREA
We have seen that brake torque is directly proportional to Piston Area, System Pressure, Friction Coefficient and Effective Radii and is not affected by pad area. Pad area and geometry are however important for several reasons:

1) Pad service life: Since pad material is consumed, an increase in pad area results in an increase in the time interval between pad replacements. OE designs often make slight sacrifices in pad life by including tapered ends for reduction of noise, vibration and pad taper. In some OE designs the pads on the two sides of the caliper are even shaped differently, with the inside pad being shorter in arc-length in the direction of rotation and wider radially than the outside pad for system design and integration reasons.

2) Heat dispersion and dissipation over a larger surface area and greater mass: Although in the case of a larger pad, the pad masks a larger portion of the rotor face, absorbing more radiant energy and shielding the area from cooling that may cancel any actual benefit.

3) Geometry: Since rubbing speed between the disc and the pad is greater at the periphery of the disc, the pad geometry will sometimes be designed to reduce the area toward the center of the disc. This is done in an effort to produce even temperature and pressure distribution across the face of the pad.

INCREASING DISC DIAMETER
The problem with increasing the effective radius of the discs is that, since the designers used the largest rotor that would fit inside the wheel. Typically, increasing the rotor diameter means increasing the wheel size. The expense involved is only one objection. A major issue is the impact on the OE suspension geometry.
The camber curves and roll resistance characteristics of any proper suspension system are designed for tires with a specific sidewall height and stiffness. Increasing the wheel diameter means decreasing the sidewall height and the compliance of the tire. Carried to an extreme, this will hurt cornering capability and might actually result in a loss of braking traction due to "edging" the front tires under heavy braking. And although technology is making possible ultra low and stylish tire side wall heights, it does not necessarily result in ultimate performance. Just take a look at the sidewall height of Formula One and Indy cars.

FLOATING DISCS
All metals "grow" when heated. The diameter of cast iron brake discs can increase by as much as 2mm (0.080 inch) at elevated braking temperatures. When the disc is radially restrained from growing (as in all one-piece discs) the friction plates are forced into a cone shape as temperature increases, adversely effecting both temperature and pressure distribution within the pads and the feel of the pedal. Racing and high performance street discs are mounted on separate hats or bells, usually of Aluminum. The fastening system is designed to allow radial growth and minimal axial float resulting in a mechanically stable system. Hats or bells should be made from heat-treated aluminum billets that are pre-stressed and relieved, not from inferior aluminum or plate stock.

SUMMARY
If the braking system is only marginal, upgrading the pads and brake fluid, and/or getting more air to the system will probably cure any problems at minimal cost. Replacing the stock rubber flexible hoses with stainless braid armored Teflon hoses will improve the ability to effectively modulate the braking force at moderate cost. When a decision is made to upgrade the braking system, make sure that the replacement components and system have been properly engineered and designed for your specific application. Ask technical questions and expect valid technical answers.

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1) Discs should have curved vanes and both greater thermal storage capacity and better airflow characteristics than OEM - otherwise you will not have achieved anything worthwhile. Depend on actual test results, not advertising claims. Discs should be mill balanced to less than 0.75 ounce-inch (54 g-cm), run-out should be less than 0.002" (0.051 mm) and thickness variation should be less than 0.0007" (0.018 mm). On race applications these tolerances are typically reduced to .25 ounce-inch, 0.0005" and 0.0001" respectively.

2) Calipers should be stiff at elevated temperature. Again, look at laboratory test results, not claims. Calipers must be mounted true to the plane of rotation of the rotor.

3) Multi-piston calipers should have differential bores to reduce taper wear. Piston area should be consistent with master cylinder size.

4) Ideally no modifications to the knuckles or uprights should be required for installation.

5) Front to rear brake torque bias should be consistent with the dynamics of the specific vehicle.

DRIVING CONSIDERATIONS

1) In order to brake effectively, the tires must comply with and grip on the road. Your braking system is no better than your tires and suspension. The best money that you can spend is on really good tires and really good shocks.

2) Proper corner weight is crucial for effective straight line braking. Optimum corner weight for braking is when the cross corner pairs are equal. That is to say the total of the left front and right rear equals the total of the right front and left rear.

3) If you smell brake lining or if the pedal starts to go soft, ease off.

4) Use at least a 550 degree non-silicone brake fluid and make sure that your brakes are bled properly and, when used hard, often. Brake fluid is hygroscopic in nature - given any chance at all it absorbs water. A fraction of one percent of entrapped water lowers the boiling point of any brake fluid dramatically - and causes corrosion within the system. Replace all of the brake fluid in the system at least once a year - more often if you constantly use the brakes hard.

by Stephen Ruiz, Engineering Manager and Carroll Smith, Consulting Engineer for Centric Parts/ StopTech

About Centric Parts®

Centric Parts®, which includes the StopTech® and Power Slot® divisions, is a leading manufacturer and supplier of aftermarket brake components and systems for everyday cars, performance duty vehicles and ultra performance vehicles. The Southern California company was founded in 2000 and now employs over 500 workers at its multiple warehouse and production facilities that total more than half a million square feet of floor space. The company's skilled and seasoned engineers and experts, and an award-winning executive team drawn from across the industry, fuel Centric Parts' mastery of the automotive aftermarket and its dedication to research and development. The patent-holding company also has one of the industry's best programs for tracking and cataloging original equipment parts and uses this expertise to devise and deliver quality aftermarket and OE parts for consumers, technicians and auto makers.

About StopTech®

StopTech®, the ultra performance and racing division of Centric Parts®, is a leading innovator of world class brake components and systems for production-based racing cars and high performance vehicles on the street and track. Founded in 1999, StopTech was the first to offer Balanced Brake Upgrades® for production cars and remains the worldwide leader with over 650 platform offerings to dramatically improve overall braking performance. StopTech's industry leading technologies and materials, from rock solid calipers to ingeniously efficient heat handling rotors, result in shorter stopping distances, better brake modulation and less brake fade.

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