Pulp Friction

A Plain-Talk Primer on Your Car's Braking System

Going fast is fun, but eventually you have to slow down. Unfortunately, many people do not fully understand how their car's braking system works, and they are quick to reengineer things in an attempt to increase performance.

So before any of us go running off to the aftermarket for our own NASCAR six-piston calipers, F1 carbon-fiber rotors, and 50 feet of stainless steel braided brake lines, it would be wise to take a deeper look into braking systems. We just might find that once we gain a fundamental understanding of what each of these components really does (and more importantly, what each does not do), we will be better prepared to make the right decisions when modifying (or choosing not to modify) our own rides.

What Do Braking Systems Really Do?

Every racer and driving enthusiast should be forced to write this on the blackboard 1000 times: "Your brakes do not stop your car." (That's 999 to go; keep writing….)

Of course, a second question then comes up: "What DO your brakes do?" In plain English, your brakes convert the energy of motion into heat; an engineer would say the brakes are responsible for turning the kinetic energy of your speeding car into thermal energy. (See the sidebar at right, "Speed vs. Heat," for more details.) But in either case, your brakes are not stopping your car.

Surprised?

So what DOES stop the car? Good question. There are many "things" that can stop your car—and several of them have nothing at all to do with your braking system. We all have experienced this first-hand as we let off the accelerator pedal and felt the vehicle begin to slow—before we ever stepped on the pedal in the middle. In theory, any one thing that can generate a force which opposes the motion of the car can and will eventually cause it to stop.

For example, the wind pushing on the front of the car, or gravity as the car climbs a hill, could cause it to lose speed and eventually stop moving. However, there are often times that we need to slow at a greater rate than what headwinds and gravity can deliver. In these cases, we depend upon the brakes to assist in the stopping process.

The next logical question then would be, "how do the brakes assist in stopping the car?" To answer, we need to look at each of the pieces of the braking system puzzle.

Speed vs. Heat

Just for fun, let's have a closer look at the equations for the conversion of kinetic energy (KE) into heat (Q):

KE = ($^1/_2$) x (vehicle weight) x (speed of the vehicle)^2

Q = (rotor weight) x (rotor material constant) x (temperature rise)

Since Mr. Isaac Newton stated that energy can be neither created nor destroyed, all of the KE from the car must be completely turned into Q. What does this tell us? KE (before) = Q (after).

Now, if we assume that…

1) the weight of the car stays constant with use;
2) the weight of the rotor remains constant with use;
3) Newton was right;

…then the "speed of the vehicle squared" is proportional (directly related) to the "temperature rise in the brakes." If you pull out your calculator, you can prove that if the speed at which the brakes are used increases by 40 percent (60 mph vs. 95 mph, for example), the temperature rise in the brakes resulting from that stop would increase by nearly 100 percent (1.4 x 1.4).

This factor is often overlooked by racers who add horsepower to their cars and can't figure out why their brakes don't seem to work as well when they "only gained 10 mph" on the straights. Lesson learned: Small changes in speed can have a huge impact on brake temperatures.

The Mighty Brake Pedal

Most *GRM* readers are probably somewhat familiar with the brake pedal. But while most of us probably think of the brake pedal only as the flat part that makes contact with the foot, remember that an equally-important component of the brake pedal assembly, the output rod, continues out of sight. Together, these parts compose the brake pedal assembly.

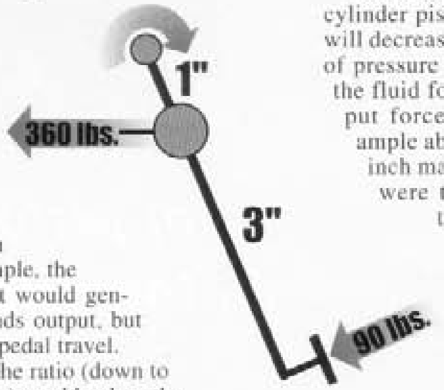
The sole function of the brake pedal assembly is to harness and multiply the force exerted by the driver's foot. It does this thanks to a concept known as "leverage." We all learned the concept of leverage on a teeter-totter—the farther you sit from the middle (the pivot), the more weight you can lift on the other end.

In the case of the brake pedal assembly, the pivot is at the top of the brake pedal arm, the pad (where we step) is on the opposite end, and the output rod is somewhere in between. In the example illustration (see Figure 1 on the next page), a driver input force of 90 pounds is multiplied by a 4:1 ratio into 360 pounds (90 lbs. x 4) of output force.

Does the output rod directly stop the car? No. So several questions now come about: Would we want to make any changes to the brake pedal, and if we did, how would this impact the brake system performance? There are several answers, each with their own set of pros and cons.

Increasing the ratio (up to 8:1, for example) would further amplify driver input force, but would make the pedal travel through a longer distance to achieve the same output. In the given example, the 90-pound input would generate 720 pounds output, but with twice the pedal travel.

Figure 1.



Decreasing the ratio (down to 3:1, for example) would reduce the overall size and weight of the brake pedal assembly, but would decrease the amount of amplification. The 360 pounds in the example would fall to just 270 pounds. To generate the same 360 pound output, the driver would need to press the pedal with 120 pounds of effort.

So, will changing the brake pedal make the car stop any faster? Not by itself. But one can tune the pedal output force and pedal travel characteristics by making changes to the pedal ratio.

The Master Cylinder

The next step in the brake system is to convert the amplified force from the brake pedal into hydraulic fluid pressure. The master cylinder, consisting of a piston in a sealed bore with the brake pedal output rod on the one side and brake fluid on the other, performs this task.

Figure 2.

As the pedal assembly output rod pushes on the piston, the piston moves within the cylinder and pushes against the fluid, creating hydraulic pressure. It's really that simple; however, in order to determine how much pressure is generated at the master cylinder, we will need to dig into a few fluid calculations. Don't flip to the classified ads just yet.

The pressure generated at the master cylinder is equal to the amount of force from the brake pedal output rod divided by the area of the master cylinder piston. If we assume a master cylinder diameter of 0.90 inches (with an area of about 0.64 square inches), the calculated pressure will be 558 pounds per square inch from the 360 pounds of pedal output force from above (360 lbs. ÷ 0.64 in.^{2}). Whew, no more math for a minute—just stare at Figure 2 for a while.

So, does this pressurized hydraulic fluid stop the car? Again, the answer is no, but like the brake pedal, making changes to the master cylinder can impact other characteristics of the brake system.

Increasing the master cylinder piston diameter will decrease the amount of pressure generated in the fluid for a given input force. In the example above, if a 1.0-inch master cylinder were to be substituted, the output pressure would fall to approximately 450 psi—a pressure reduction of nearly 20 percent for a 0.1-inch increase in diameter. Small changes here make a big difference.

Decreasing the master cylinder piston diameter works the same principle in reverse. Swapping in a 0.80-inch master cylinder will increase pressure to over 700 psi—this time a 25 percent increase for a 0.1-inch decrease in diameter.

Given the relationship between master cylinder piston diameter and hydraulic force, it may seem desirable to use the smallest master cylinder possible. However, since there will always be some compliance (see the sidebar above) within the system, the braking system has to have enough additional hydraulic fluid on hand to fill all the extra volume caused by the flexing of components during the compliance phase.

Unfortunately, this is accomplished by increasing the diameter of the master cylinder—which, we just learned, reduces the pressure generated. Therefore, one has to make sure that the master cylinder has a large enough diameter to meet the fluid volume requirements of the system, but is small enough to generate the pressure required. (There's never an easy answer, is there?)

The Brake Tubes and Hoses

On the surface, the brake tubes and hoses have one of the easiest jobs in the braking system: transporting the pressurized brake fluid away from the master cylinder to the four corners of the car. It would be ideal to use the most rigid material possible to minimize the compliance in the system. However, since the braking components at the wheels (calipers, pads, and rotors) are usually free to move around with the wheels and tires, a flexible portion is required—and flex equals compliance.

Traditionally, auto manufacturers have used rigid steel tubing to get the fluid almost all the way there, and a short length of rubber-coated nylon tubing to make the connection to the moving stuff, but even this short section of flexible tubing can cause significant compliance in a racing application.

For this reason, we racers prefer to replace the rubber hose with a nylon tube covered by stainless steel braiding. Most people notice the reduction in brake pedal travel due to the reduced compliance immediately, but it usually depends on how old and compliant the old rubber-coated hoses were at the time of replacement.

Although those cool-looking stainless steel brake lines alone will not make your car stop any faster, the decrease in compliance and improvement in pedal feel can make a driver much more confident. They will probably provide some increased level of resistance to damage from flying debris as well. Did we mention they look cool?

The Caliper

The caliper is one of the most familiar components to the racer, yet sometimes the most misunderstood. Like the master cylinder, the caliper is just a piston within a bore with pressurized fluid on one side. While the master

Compliance

The first conclusion people come to when seeing all this brake talk is "I'll get the smallest brake pedal I can find, put it in the car, and make up for the decrease in pedal force amplification with a very small master cylinder." Close, but in the real world there is another factor at work that should affect your decision: compliance. As pressure begins to build in the braking system, the various components in the system will flex until all clearances have been taken up. During this time, seals, clearance parts and other flexible components will stretch and deform, effectively increasing the hydraulic volume in the brake system.

To picture this, imagine blowing up a balloon inside a pop can. The balloon will expand freely until it comes in contact with the sides of the can. This is the stage of compliance, and the bigger the can, the greater the compliance. Once the balloon has taken up the volume of the can completely—similar to the brake system components completing their flexing—it gets much, much harder to blow more air into the balloon. This is the stage of pressurization.

In the braking system, compliance is highly undesirable because it requires extra hydraulic fluid to fill this increased volume before pressure can build. In the pop can analogy, one would want the smallest pop can possible in order to minimize the amount of time required to get past the compliance stage and directly into the pressurization stage.

You could say that in this case, non-compliance is best.

cylinder used mechanical force on the input side to create hydraulic force on the output side, the caliper does the opposite by using hydraulic force on the input side to create mechanical force on the output side. The top view shown in Figure 3 (right) illustrates how the pressurized brake fluid working against the back side of the piston is converted into a squeezing or clamping force.

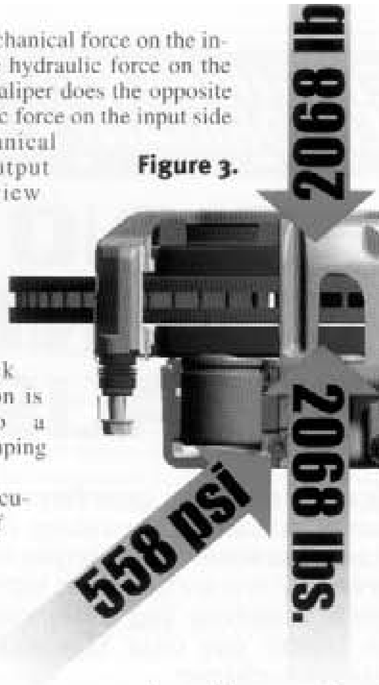


Figure 3.

In order to calculate the amount of clamping force generated in the caliper, the incoming pressure is multiplied by the area of the caliper piston. In our example, the 558 psi that had been generated at the master cylinder has traveled through the brake pipes and lines and is pushing against two 1.5-inch pistons per caliper. Therefore, the effective area of the caliper will be equal to two times the area of a single 1.5-inch piston. Working the numbers reveals that 558 psi will generate 2068 pounds of clamp load (558 psi x 1.84 in.^{2} x 2).

As you have probably already guessed, increasing the caliper piston diameter increases the clamp load for a given input pressure—but again, this does not stop the car. Putting on bigger calipers might seem like a good idea at first, but the tradeoffs might make you think twice.

Increasing the diameter will increase the compliance in the system. (Bad news for pedal feel!)

Increasing the diameter will increase the size and weight of the caliper. (Bad news for unsprung weight!)

Increasing the diameter will increase the fluid volume requirement of the system. (Bad news for master cylinder sizing!)

So, when thinking about that big six-piston caliper conversion, keep in mind that the size and number of caliper pistons on your car were originally matched to the brake pedal and master cylinder to generate an appropriate clamp load for a given brake pedal input force. Changing any one of the components will shift the balance one way (increased pressure required) or the other (higher pedal forces required) to generate the same clamp load. Remember: Bigger calipers don't create any more "stopping power" and they do not "decrease stopping distance"—they just generate higher clamp loads for a given pressure input.

One final caliper note of interest: You may have heard the terms "fixed caliper" (indicating that the caliper body is bolted directly to the suspension upright) and "floating caliper" (indicating that the caliper body is free to float on sliding guide pins). Although there are pros and cons associated with each type, there is not enough room in this article to dig into the details of their design differences. For now, let it suffice to say that the above math works out the same for either design.

So, to this point, our example brake pedal, master cylinder and caliper have amplified the original 90 pounds of driver input to over 2000 pounds—an increase of more than 22 times, but we still haven't stopped the car.

The Brake Pads

This part might surprise some and offend others, but it is a big misconception that changing brake pad material will magically decrease your stopping distances. In fact, you may have even seen published "data" which attempts to correlate stopping distance to friction coefficient. Although it may appear that there is a relationship between the two, there really isn't, and here's why.

The brake pads have the responsibility of squeezing on the rotor (a big steel disc which is mechanically attached to the road wheel) with the clamping force generated by the caliper. There is a lot of black magic surrounding the material composition and formulation of the friction puck, but what really matters is the effective coefficient of friction between the brake pad and the rotor face.

By knowing the clamp load generated by the caliper and the coefficient of friction between the pad and rotor, one can calculate the force acting upon the rotor. In this particular example, let's assume the brake pads

Those Poor Rotors

Let's look at some common rotor "modification" and "performance" upgrades that you may have been exposed to. We'll try to separate the marketing from the engineering:

Bigger rotors will make your friends think you are cool, bigger rotors look sexy, but bigger rotors do not stop the car. What a bigger rotor will do is lower the overall operating temperature of the brakes—which is a GREAT idea IF your temperatures are causing problems with other parts of the braking system.

Take, for example, a Formula 500 racer, a small 800-pound, single-seat formula car. While the brakes are certainly much smaller than those found on a 3000-pound GT1 Camaro, that does not necessarily mean that they need to be made larger. In fact, installing a GT1 brake package onto our formula car would probably do more harm than good. That's a lot of steel hanging on the wheel that needs to accelerate each time the gas pedal is pushed. So the motto of this story is bigger is better until your temperatures are under control. After that point, you are doing more harm than good, unless you really like the look. (And hey, some of us do.)

Crossdrilling your rotors might look neat, but what is it really doing for you? Well, unless your car is using brake pads from the '40s and '50s, not a whole lot. Rotors were first drilled because early brake pad materials gave off gasses when heated to racing temperatures, a process known as "gassing out." These gasses then formed a thin layer between the brake pad face and the rotor, acting as a lubricant and effectively lowering the coefficient of friction. The holes were implemented to give the gasses somewhere to go. It was an effective solution, but today's friction materials do not exhibit the same gassing out phenomenon as the early pads.

For this reason, the holes have carried over more as a design feature than a performance feature. Contrary to popular belief, they don't lower temperatures. (In fact, by removing weight from the rotor, they can actually cause temperatures to increase a little.) These holes create stress risers that allow the rotor to crack sooner, and make a mess of brake pads—sort of like a cheese grater rubbing against them at every stop. Want more evidence? Look at NASCAR or F1. You would think that if drilling holes in the rotor was the hot ticket, these teams would be doing it.

The one glaring exception here is in the rare situation where the rotors are so oversized that they need to be drilled like Swiss cheese. (Look at any performance motorcycle or lighter formula car, for an example.) While the issues of stress risers and brake pad wear are still present, drilling is used to reduce the mass of the parts in spite of these concerns. Remember that nothing comes for free. If these teams switched to non-drilled rotors, they would see lower operating temperatures and longer brake pad life, at the expense of higher weight. It's all about tradeoffs.

Slotting rotors, on the other hand, might be a consideration if your sanctioning body allows for it. Cutting thin slots across the face of the rotor can actually help to clean the face of the brake pads over time, helping to reduce the glazing often found during high-speed use which can lower the coefficient of friction. While there may still be a small concern over creating stress risers in the face of the rotor, if the slots are shallow and cut properly, the trade-off appears to be worth the risk. (Have you looked at a NASCAR rotor lately?)

have a coefficient of friction of 0.45 when pressed against the rotor face. The rotor output force is equal to the clamp force multiplied by the coefficient of friction (which is then doubled because of the "floating" design of the caliper), or in this case 2068 pounds x 0.45 x 2 = 1861 pounds. Nothing magical about it.

By increasing the coefficient of friction of the brake pads, the results are the same as increasing the caliper piston diameter—higher forces will be generated for the same input. But as before, this force is not what stops the car.

So why change brake pad materials in the first place? Because increasing the coefficient of friction can allow for the use of smaller/fewer caliper pistons and/or will reduce the amount of pedal force that the driver needs to apply in order to generate a given rotor output force.

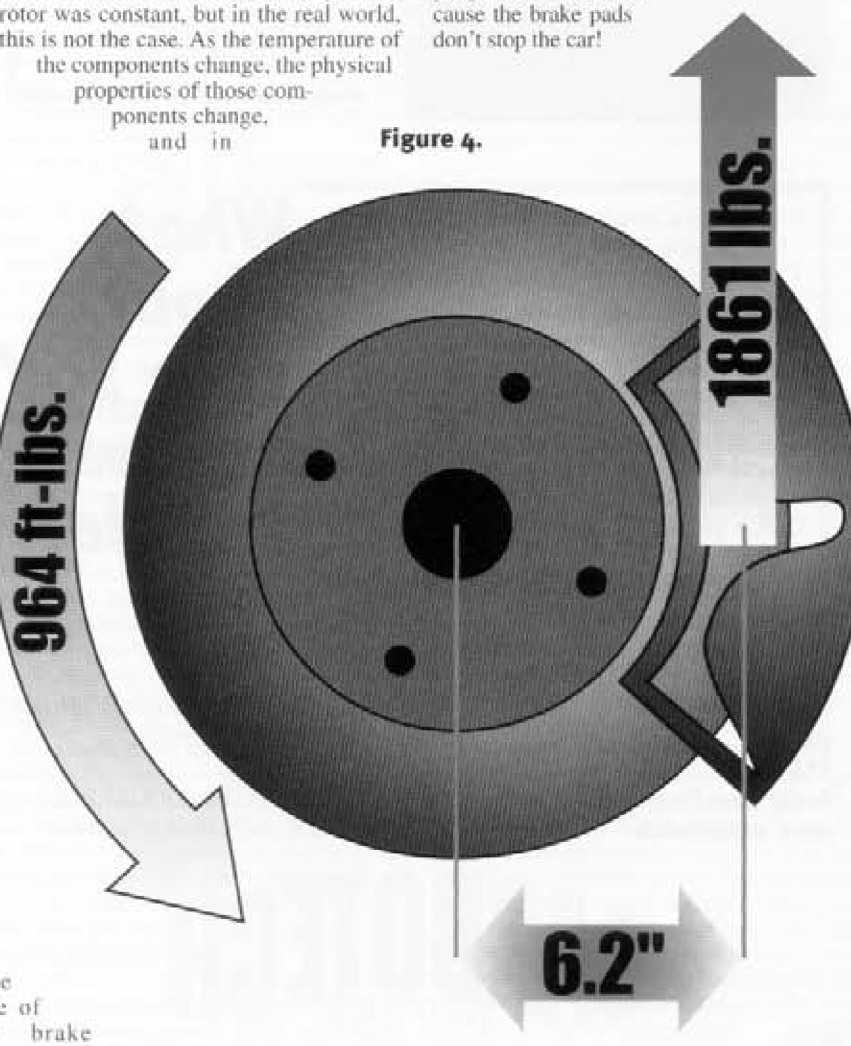
That's about it from a design standpoint, but the racer has another point to consider: heat. In the example above, the rotor output force was calculated assuming that the coefficient of friction between the brake pad and the rotor was constant, but in the real world, this is not the case. As the temperature of the components change, the physical properties of those components change, and in the case of the brake pads, the coefficient of friction can change dramatically.

While street pads might have a coefficient of 0.30 around town, after a few laps on the track, the coefficient can drop to below 0.10, a condition commonly known as "brake fade." (Note: This should not be confused with brake fluid fade, which results from water in the brake fluid turning to vapor at high temperatures.) On the race track, this means that the brake pedal force required to stop changes from lap to lap. And as racers, we know this can be kind of, well, unsettling, to say the least.

So, back to the black art of friction materials. While a "coefficient of friction" number is a nice data point to consider when modifying a braking system, what is even more important is the ability of the material to maintain that coefficient under a variety of driving conditions.

Brake pads with radical changes in coefficient over their operating range are not a racer's best friend. Be sure to select one that remains relatively stable under the operating conditions you are expecting, but don't expect any shorter stopping distances, because the brake pads don't stop the car!

Figure 4.



The Rotor

The rotor actually stops the car—just kidding. Like the other parts of the system mentioned so far, the rotor (Figure 4, above) does not stop the car; however, unlike the other braking system components, the rotor serves two purposes, listed here in order of appearance:

The rotor acts as the frictional interface for the brake pads. But because it is a spinning object, it reacts to the output force by absorbing the torque created. (Any time a force is applied to a spinning object, a torque is generated.) In this case, if we assume the force to act at a point midway across the rotor face (6.2 inches from the center of rotation in our example) then the torque is equal to about 964 ft.-lbs. (1861 pounds x 6.2 inches ÷ 12 inches per foot).

The rotor must also absorb the heat generated by the rubbing of the brake pads against the rotor face.

In the case of the second item above, the rotor dissipates the heat generated by warming the air surrounding the rotor. This is why brake cooling ducts are so useful. Where does the torque go? The 964 ft.-lbs. sure is a lot of torque, and it has to go somewhere. (But, before YOU go any further, you might want to check out the sidebar on page 77, "Those Poor Rotors").

The Wheels and Tires

Time to get down to business—and time to stop the car. Because the wheel and tire are mechanically bolted to the rotor, the torque is transferred through the whole assembly: rotor, hub, wheel and tire. And now, the moment we have all been waiting for:

It is the interface between the tire and the road that reacts to this torque, generating a force between the tire and the road that will oppose the motion of the vehicle. The math looks just like the equation to calculate the torque in the rotor, but in reverse. (See Figure 5, too.)

Crunching the numbers based on a 275/35R17 tire with a rolling radius of 12.2 inches shows that a force of 942 pounds is generated between the tire and road, opposing the motion of the vehicle.

Ladies and gentlemen, this is what stops the car—not the brake pads, not the rotors, not the cool stainless steel brake lines. It's the road reacting against the tire.

Now, in order to finish the job, all that is necessary is to add up all the forces (remember, there is a force acting on every wheel with a brake) and run through a little more math. In case you haven't noticed, we engineers just love this math stuff.

Adding the Forces

As that famous guy Newton said, force = mass x acceleration (F=MA). Or, stated another way, the acceleration (or deceleration as the case may be) of an object will be equal to the sum of all of the forces acting on the object divided by the weight of the object.

Before we can sum up all the forces, there is one last little important fact to consider: The tire forces are not the same for the four corners of the car. Due to the static weight distribution of the car, the location of the center of gravity of the car, and the effects of dynamic weight transfer under braking (just to name a few), the rear brakes are designed to generate much smaller forces than the forces generated by the front brakes. For the sake of argument, and for this exercise, we'll say the split is 80 percent front and 20 percent rear, but the actual distribution is dependent on the specific vehicle configuration.

So, if each front tire generates 942 pounds of force, then we can calculate that each rear tire generates 20 percent of that, or 188 pounds. Adding up the four corners now gives us a total of 2260 pounds of force acting on the vehicle between the four tires and the road.

Rearranging Newton's home run mentioned above, (decel = force ÷ weight), we can calculate that the total deceleration of the vehicle is 0.84g, or 2260 pounds force ÷ 2640 pounds weight. Easy, right?

Calculating the Distance

Okay, last equation of the day. Given a vehicle speed of, say, 100 miles per hour, and the deceleration level from above, we can now calculate the distance required to bring the car to a stop. But, in order to make sure the answer comes out in feet, we first need to juggle the numbers around a little bit:

100 miles per hour = 147 feet per second

0.84g = 27.0 feet per second per second

Apply the equation for stopping distance {distance = (initial speed)^2 ÷ (deceleration x 2)} and lo and behold, exactly 400 feet are required to bring this car down to a stop from 100 miles per hour given our original pedal input force of 90 pounds. Tah dah! The car is now stopped.

Limiting Factors

From this example, it would appear that in order to make the car stop in a shorter distance, there are two options:

1) Change the brake system to increase the force between the tire and the road for a given pedal input force.

2) Press on the brake pedal harder.

This theory holds true, but only up to a point. Anyone who has even driven on an icy road will get this right away. As the brake pedal force is gradually increased, the deceleration rate will also increase until the point at which the tires lock. Beyond this point, additional force applied to the brake pedal does nothing more than make the driver's leg sore. The vehicle will continue to decelerate at the rate governed by the coefficient of friction between the tires and the road. As you can imagine, the coefficient of a given tire on ice is much lower than the coefficient of that same tire on dry pavement, hence the increased deceleration possible on the dry, paved surface.

You can take this one to the bank. Regardless of your huge rotor diameter, brake pedal ratio, magic brake pad material, or number of pistons in your calipers, your maximum deceleration is limited every time by the tire to road interface. That is the point of this whole article. Your brakes do not stop your car. Your tires stop the car. So while changes to different parts of the brake system may affect certain characteristics or traits of the system's behavior, using stickier tires is ultimately the only sure-fire method of decreasing stopping distances.

So, Why Would Anyone Want to Modify Their Brakes?

If changing braking system components does not provide increased stopping power or shorter stopping distances, why even consider changes in the first place? Why not just leave the brakes alone and buy new tires? Quite simply, making changes to your braking system can have a very real, very significant impact on four areas of brake system performance other than stopping distance:

1) Driver tuning: Modifying your brake system component sizing (brake pedal ratio, master cylinder piston diameter, caliper piston diameter, rotor diameter) can be performed to adjust the feel of the car to suit the driver's tastes. Some drivers prefer a high, hard pedal, while others prefer a longer stroke. In this regard, tuning your brakes is a lot like tuning your shocks: every driver likes something different, and there is no right answer within certain functional limits. These components can be adjusted in small steps to achieve a feel that the driver prefers.

2) Thermal control: Modifying your brake system mass (rotor weight) can be used if there is a thermal concern in the braking system. If your brakes work consistently under your driving conditions, then adding "size" to the braking system will accomplish nothing more than increasing the weight of your vehicle. But if high temperatures are having an adverse effect on braking system performance or other components in general—wheel bearings, for example—then you should consider super-sizing. Of course, brake cooling ducts can really help out here as well.

3) Temperature sensitivity: Modifying your brakes to address the presence of high temperatures (brake pad material and brake fluid composition) should only be considered if your thermal concerns cannot be resolved by super-sizing. This is really just a Band-Aid for undersized systems, like those found on Showroom Stock race cars that are not permitted by their rules to upsize or cool their brakes. One might argue that it is more cost-effective to install better brake pads and brake fluid than it would be to upsize the rotors, but all that heat still needs to go somewhere—and more often than not it will find the next weak link in the system.

4) Compliance: Any changes that you can make to your braking system to reduce compliance will increase the overall efficiency of the system—improving pedal feel, wear, and stop-to-stop consistency. Think of it as balancing and blueprinting your braking system.

Brake system modifications have their place to help make your ride more consistent, predictable, and user-friendly; however, if your ultimate goal is to decrease your stopping distance, look no further than the four palm-sized patches of rubber connecting your ride to the ground.

James Walker, Jr. of scR motorsports races a 1992 Saturn SC in the SCCA's ITA class. His real job as an anti-lock braking systems engineer with the Robert Bosch Corporation has him applying these very same brake system principles on a day-to-day basis. To find out more about his scR motorsports race team, visit www.teamscR.com.