TDReview

TDReview is a review of an article or evaluation of a product for your Turbo Diesel.

As a subscriber to a number of publications, your editor happened upon an article on braking systems in Grassroots Motorsports. As I searched for an answer to better brake performance, I realized that I was concentrating my efforts (read: money) somewhat in the wrong direction. After reading author James Walker's article, I knew that I had to get this information to the TDR audience. I made some phone calls to inquire, and now I am pleased to present James' article complete with some custom tweaks for us, the Turbo Diesel audience.

BRAKING SYSTEMS IN PLAIN ENGLISH

By James Walker, Jr. of scR motorsports

Readers of this publication often see advertisements describing brake upgrades available to diesel enthusiasts. However, 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. You just might find that once you gain a fundamental understanding of what each of these components **really** does (and more importantly, what each does **not** do), you will be better prepared to make the right decisions when modifying (or choosing not to modify) your own rides.

WHAT DO BRAKING SYSTEMS REALLY DO?

So, here comes the first surprise. Your brakes do not stop your truck. The traction available between the road and the tire's four contact patches—where the rubber meets the road, so to speak—is the limiting factor when everything comes to a halt. For all intent and purposes, this could complete our article, but because a two paragraph story doesn't read too well, I suppose we should continue to discuss the actual purpose of the braking system.

Of course, the next question is: "What do the 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 truck into thermal energy. The engineer would also be able to tell us (kind of funny, but I am an engineer myself) that for every percent increase in vehicle weight, there is a equal percent increase in the amount of energy, and consequently, heat generated. For example, load up your 5000 pound truck to 8000 pounds (an increase of 60%) and your brakes will run 60% hotter, everything else being equal.

Even more interesting is the relationship between speed and heat. Unlike the one-to-one relationship with vehicle weight, the heat goes up with the increase in speed squared. In other words, if you make a stop in your truck from 45mph and another from 65mph (an increase of 44%), the amount of heat would increase by 209%! Little changes in speed make a big difference in heat, and as we will find out later, heat is usually the enemy.

Now let's look at each of the pieces of the braking system puzzle to understand just exactly how they convert the energy of motion into heat, and how this process results in tire traction stopping the truck.

Author's disclaimer: while the concepts, analysis, and functional descriptions of the brake system components described herein are 100% applicable to the TDR reader, the actual sizes and physical relationships used in this example are not from an actual Dodge product. Many of the values are from my race car, but the rest were chosen to make the math easy.

THE MIGHTY BRAKE PEDAL

I'm hoping that you are all 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 part of the brake pedal assembly, the output rod, continues out of sight. Together, these parts constitute 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 (Figure 1), a driver input force of 90 pounds is multiplied by the 4:1 ratio into 360 pounds {90 lb. x 4} of output force.

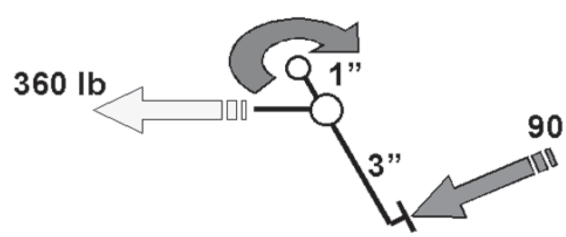

Figure 1 – The brake pedal as a simple lever

Does the output rod directly stop the truck? No. So would you want to make any changes to the brake pedal, and if you 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 (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.

- Decreasing the ratio (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 truck stop any faster? Not by itself. But while one can tune the pedal output force and pedal travel characteristics by making changes to the pedal ratio, these parts (because of their complexity) are rarely found in the aftermarket.

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. In addition, on most diesel-powered vehicles there is an auxiliary power supply unit commonly known as HydroBoost lumped into the assembly.

HydroBoost uses power steering fluid under pressure to increase the force coming from the brake pedal output rod before it pushes against the master cylinder piston. 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 (plus the HydroBoost contribution, say, an additional 325 pounds, for a total of 685 pounds) divided by the area of the master cylinder piston. If we assume a master cylinder diameter of 1.25 inches (with a resulting area of about 1.23 square inches), the calculated pressure will be 558 pounds per square inch (PSI) from the 685 lbs. of output force from above (685 lb. ÷ 1.23in^2).

Whew—no more math for a minute, just stare at Figure 2 for a while.

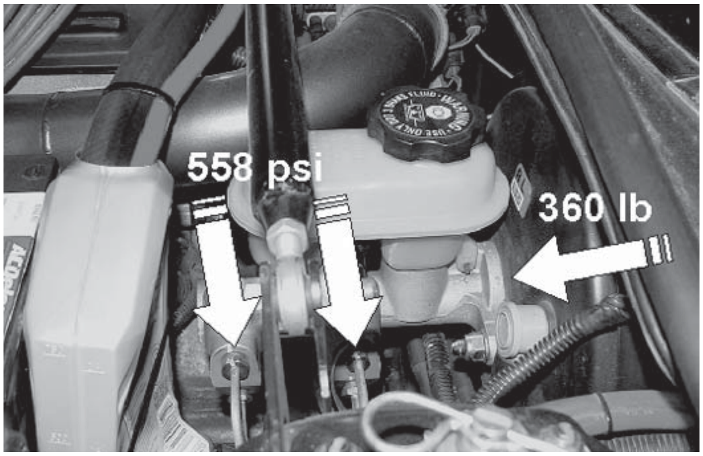

Figure 2 – The master cylinder generating pressure

So, does this pressurized hydraulic fluid stop the truck? 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. Seems backwards, but that's the way it works out. In the example above, if a 1.375" master cylinder were to be substituted, the output pressure would fall to approximately 460 PSI—a pressure reduction of nearly 20% for a +0.125" change in diameter. Small changes here make a big difference.
- Decreasing the master cylinder piston diameter works the same principle in reverse. Swapping in a 1.125" master cylinder will increase pressure to just about 700 PSI—this time a 25% increase for a -0.125" change 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, 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 (this is one reason that the brake fluid reservoir is so large as well). 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 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 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 significantly affect compliance. For this reason, it is sometimes preferred to replace the rubber hose with a nylon tube covered by stainless steel braiding (see Figure 3). Most people notice the reduction in brake pedal travel due to the reduced compliance immediately, but it usually depends on how old and flexible the old rubber coated hoses were at the time of replacement.

Figure 3 – Stainless steel brake hoses

Although those cool-looking stainless steel brake lines will not make your truck stop any faster on their own, 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 I mention they look cool?

THE CALIPER

The caliper is one of the most familiar components, 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 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 4 illustrates how the pressurized brake fluid working against the back side of the piston is converted into a squeezing or clamping force.

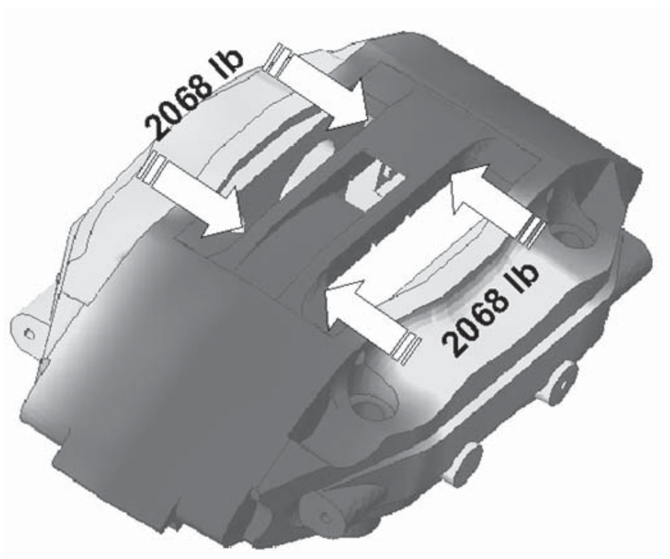

Figure 4 – Caliper clamping force

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 lines and hoses and is pushing against two 1.5" pistons per caliper. Therefore, the effective area of the caliper will be equal to two times the area of a single 1.5" piston. Working the numbers reveals that 558 PSI will generate 2,068 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 truck. Putting on bigger calipers might seem like a good idea at first, but the tradeoffs might make you think twice:

- Increasing the piston diameter will increase the compliance in the system (bad news for pedal feel!)
- Increasing the piston diameter will increase the size and weight of the caliper (bad news for unsprung weight!)
- Increasing the piston diameter will increase the fluid volume requirement of the system (bad news for master cylinder sizing!)

So, when thinking about that big-piston caliper conversion, keep in mind that the size and number of caliper pistons on your truck 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, in our example the brake pedal, master cylinder, and caliper have amplified the original 90 pounds of driver input to over 2,000 pounds—an increase of more than 22 times—but we still haven't stopped the truck (keep thinking traction, traction, traction).

THE BRAKE PADS

This part might surprise some and offend others, but there 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. 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 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 {2,068 pounds x 0.45 x 2} = 1,861 pounds (see Figure 5). 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 alone is not what stops the truck (remember: traction, traction, traction). 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.

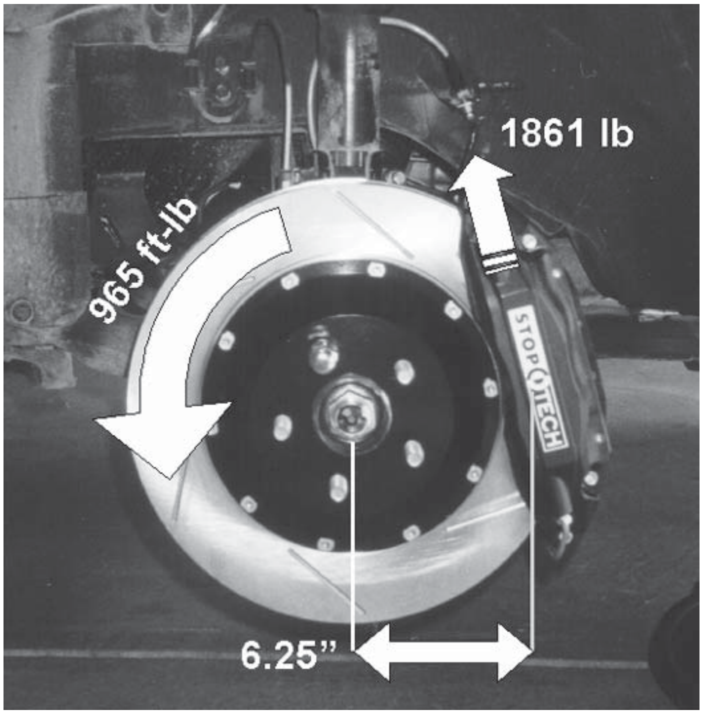

Figure 5 – The brake corner in action

That's about it from a design standpoint; however, there is a final 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 changes, and in the case of the brake pads, the coefficient of friction can change dramatically! While pads might have a coefficient of 0.45 around town, after a few trips down the mountain and fully loaded, 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.) If you have ever experienced brake fade firsthand, you 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 temperatures brought on by driving and towing conditions. Brake pads with radical changes in coefficient over their operating range are not your 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 truck!

THE ROTOR

The rotor actually stops the truck—just kidding! Like the other parts of the system mentioned so far, the rotor does not stop the truck; however, unlike the other braking system components, the rotor serves two purposes. In order of appearance, they are:

1) 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" from the center of rotation in our example) then the torque is equal to about 964 ft-lb. {1,861 pounds x 6.2" ÷ 12 inches per foot}. Take a second look back at Figure 5 to follow along.

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

In the case of item (2) above, the rotor dissipates the heat generated by warming the air surrounding the rotor (this is why brake cooling ducts are so useful), but where does the torque go? The calculated 964 ft-lb. sure is a lot of torque (most diesel owners would appreciate those kinds of torque numbers), and it has to go somewhere. . .

THE WHEELS AND TIRES

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

It is the traction 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 truck. The math looks just like the equation to calculate the torque in the rotor, but in reverse. Crunching the numbers based on a 275/35R17 race tire with a rolling radius of 12.2 inches (there go those race car numbers sneaking back into a TDR article again) 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 truck—**not** the brake pads, **not** the rotors, **not** the cool stainless steel brake lines—it's road reacting against the tire!

Now, in order to finish the article, all that is necessary is to add up all the forces (remember, there is a force acting on every tire 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 truck. Due to the static weight distribution of the truck, the location of the center of gravity of the truck, 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% front and 20% 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% 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 homerun mentioned above, {decel = force ÷ weight}, we can calculate that the total deceleration of the vehicle is about 0.85g's, or {2260 pounds force ÷ 2640 pounds weight}. Easy, right? Figure 6 wraps it all up for us.

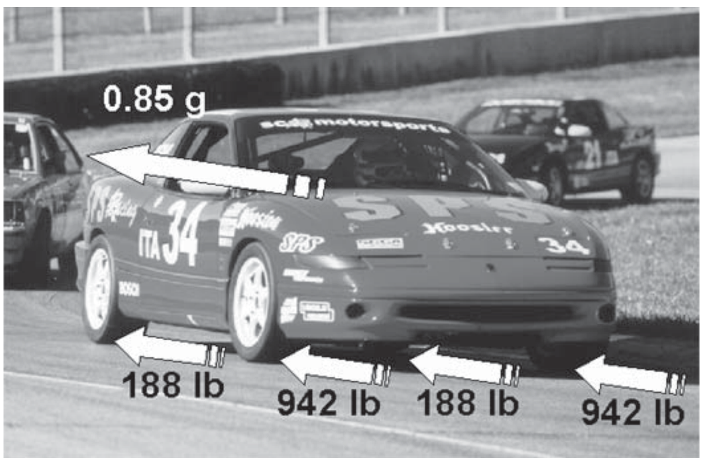

Figure 6 – Look! A real race car!

Doing a little backwards math here that TDR readers will appreciate, we can calculate that if our vehicle is generating 2260 pounds of force through tires that are 24.2 inches tall, our braking system has created 2223 foot-pounds of torque. Can that possibly be right?

While this may sound like an unreasonable number, these torque levels are commonplace in braking system design and analysis. It takes torque to accelerate, but it also takes torque to decelerate. Consider that a typical unloaded truck can easily stop from 60mph in well under four seconds on dry pavement (assuming adequate traction). In contrast, just imagine how much engine torque it would take to accelerate your truck from rest to 60mph in that same sub-four second window. Yes, there is a transmission and final drive reduction in the acceleration equation, but in nearly every case factory braking systems are designed to generate more torque than the factory powertrain is capable of producing.

Brake guys chuckle to themselves when engine guys brag about their torque output.

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 truck 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
0.85g's = 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 truck down to a stop from 100 miles per hour (given our original pedal input force of 90 pounds). Tah dah! The truck is now stopped.

LIMITING FACTORS

From this example, it would appear that we might be able to make the truck stop in a shorter distance. Let's investigate these two options further:

- Change the brake system to increase the force between the tire and the road for a given pedal input force
- Press on the brake pedal harder

These two changes will shorten the truck stopping distances for sure, but only up to a point. Anyone who has ever 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 run out of traction and lock up**. 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 traction between the tires and the road. As you know, the traction of a given tire on ice is much lower than the traction of that same tire on dry pavement. This is exactly why stopping distances are longer on slippery surfaces.

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 the 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 truck. Your tires stop the truck. So while changes to different parts of the brake system may affect certain characteristics or traits of the system behavior, using better tires is ultimately the only sure-fire method of decreasing stopping distances.

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SO WHY WOULD ANYONE WANT TO MODIFY THEIR BRAKES?

So, if changing braking system components does not provide shorter stopping distances, why even consider changes in the first place? Why not just leave the brakes alone and buy new tires? Well, as we have implied earlier in this article, making changes to your braking system can have a very real, very significant impact on four other areas of brake system performance (other than stopping distance).

- 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 truck 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.

- Thermal control. Modifying your brake system mass (rotor weight) can be utilized 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". Naturally, other constraints (wheel diameter, for example) may make super-sizing impossible, but adding rotor weight is the best way known to reduce brake temperatures. Figure 7 shows just how far one car go!

- Temperature sensitivity. Modifying your brakes to address the presence of high temperatures (brake pad material and brake fluid composition) should be considered if your thermal concerns cannot be resolved by super-sizing. This is really just a Band-Aid for undersized systems. 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.

- 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.

Figure 7 – Filling the wheel with brake hardware

In summary, 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
TDR Writer

ABOUT THE AUTHOR

James Walker, Jr. of scR motorsports races a 1992 Saturn SC in the SCCA's ITA class. With a degree in vehicle dynamics, his brake systems background has included tours of duty with Delphi, TRW, GM, Bosch, and the Ford Motor Company. And, when spare time allows, he serves as a consultant to STOPTECH, an industry leader in high-performance braking systems. To find out more about James and his team, visit their website at www.teamscR.com.

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