Braking System Basics and Modifications, Illustrated With a Guide for Improving the Brakes of the Porsche 964

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Originally published by Porsche Club of America in *Porsche Panorama*, June and July 2005

Up-fixin der Porsche has always been a popular activity, particularly since Porsche cars are easily updated with parts from other model Porsches. The braking system of many owners Porsche has long been a target for an up-fixin project, from the 1950's when it was not uncommon to fit a garden variety 356 with the brakes from a 550 Spyder, to today's fitting of a Turbo model's so-called "Big Red" brakes to a non-Turbo 911.

Many misconceptions exist regarding braking systems however, and this article discusses the basics of braking system operation, the reasons to consider an upgrade and, using the 964 model as an example, show how options for parts interchangeability can be used to upgrade this model's brakes.

Braking System Basics

The braking system of the automobile is a friction device designed to convert the kinetic energy of the moving vehicle into heat which is dissipated into the air. This heat produced by braking is directly related to the mass and to square of the speed. That is to say, if the vehicle's mass (weight) is doubled, the heat produced by braking is also doubled, but if the speed is doubled, the heat is *quadruple*d. This effect of speed on the amount of heat dissipated is the reason higher performance model Porsche cars such as the Turbo, RS, and racing versions have larger, or different design brakes.

The Role of The Tire in Stopping the Car

It *is really the frictional adhesion of the tire contact patch to the road (tire grip) that stops the car, not the brakes*. *The brakes only stop the tire from rolling*.

The tire's frictional adhesion is related to the vertical force (load) on the tire contact patch and the area of the contact patch. *The more weight supported by a tire and the larger it's contact patch the greater its braking capacity will be.*

A tire's coefficient of friction (at a given contact patch size) is the ratio of the horizontal sliding force divided by the vertical force (load). For example, if a tire has a load of 100 pounds and starts to slide at an applied horizontal force of 90 pounds, the coefficient of friction is 0.9. The higher the coefficient of friction, the more "grip" a tire has.

As a tire rotates, it is really placing the contact patch continuously ahead of itself without any relative sliding occurring. As the contact patch is stressed by a horizontal force such as braking (or cornering) it *achieves the greatest coefficient of friction when a small percentage of slip against the road occurs* to heat the tire. This is the principle so called: "threshold braking" is based on. One must maintain each tire at the highest coefficient of friction with only a small amount of actual sliding occurring relative to the road.

A given tire's coefficient of friction is dependent on tread temperature and surface loading. The coefficient tends to increase with increasing temperature up to a point, usually around 200 to 220 degrees F. when it then begins to drop. This means to produce the greatest stopping ability the tire must be at its optimum temperature.

The coefficient of friction of rubber is also improved by lower surface loading. This means the lower the number of pounds per square inch the tire contact patch is supporting, the higher the coefficient of friction will be. So, everything else being equal, increasing the surface area of the tire contact patch will improve braking performance.

A tires coefficient of friction is also dependent on the chemical properties of the rubber in the tread compound of the tire. A "sticky" racing tire has a higher coefficient of friction than a normal street tire and a car will stop faster with a racing tire.

Designing a braking system requires a balancing of the torque (a "torque" is a force applied in rotation) forces produced by the tire and brake working against one another in opposite directions, these two forces are: *wheel torque and brake torque.* This couple of forces is called the "braking couple".

Tire Torque

When the vehicle moves, the lever between the tires contact patch and the axle center (tire radius) produces a torque which turns the tire. The maximum amount of torque attainable is proportional to the tire's coefficient of friction, the radius (length of lever) of the tire and the momentum of the car.

Brake Torque

The disc brake system is comprised of two basic components at each wheel called the disc and the caliper. Seen through the wheel opening in the photo, the disc is the grayish-colored part with holes in it and the caliper is the red piece seen wrapped around a segment of the disc.

The disc is connected to, and turns with, the wheel while the caliper is fixed to the chassis through the suspension links. A caliper is simply a clamp in which there are, on opposite sides of the disc, friction surfaces (brake pads) which are pressed against the disc when the driver pushes the brake pedal. In response to pedal pressure, the pads pinch the disc producing a friction that resists rotation of both the disc and the attached tire, producing heat within the disc and caliper. The brake friction works on a lever applied from the pad center to the center of the axle called the "working radius" of the disc *producing the brake torque in the <u>opposite direction</u> to the tire torque.* Eventually the tire's contact friction is overcome and the tire slides across the pavement when brake torque equals wheel torque unless prevented by anti-lock brakes or reduction in pressure on the brake pedal by the driver.

The brake system needs to be designed to match brake torque to tire torque in order to achieve maximum braking effect; in other words for maximum deceleration, the brake couple needs to be matched at all 4 wheels during brake application.

Matching the Braking Couple- A Sometimes Difficult Marriage

The tire is producing torque applied on the tire radius and the clamped disc is producing a countering torque applied on the disc radius.

Imagine a turnstile with two people pushing in opposite directions, whether the turnstile rotates and the direction it rotates depends on the strength of the people pushing the turnstile. A weaker person could be given an advantage by increasing the length of the turnstile arm on their side to overcome the strength advantage of the other person.

The brake system designer controls three variables in design of the braking system in order to tune the braking couple at each wheel:

1) The clamping force generated by the caliper on the disc.

2) The coefficient of friction of the brake pad material.

Note: This is essentially identical in concept to the tire coefficient of friction, but brake pad material is different than rubber. Rubber physically interacts with the road surface and it's coefficient of friction is *sensitive* to surface loading while brake pad material merely rubs against the rotor not physically interacting with it and therefore its coefficient of friction is *insensitive* to surface loading*, therefore fitting larger pads does not increase brake torque*.

3) The diameter of the disc that the caliper clamping force is applied to.

The clamping force applied to the disc is first dependent on the force applied by the driver against the brake pedal. This brake pedal force is applied to the brake pedal lever pivoting in the car against the master cylinder piston which increases the fluid pressure in the system of tubes distributing fluid pressure to the calipers. The calipers in turn have pistons in them which move in response to this fluid pressure and push the pads against the disc. The force multiplication that occurs in this series of events is dependent on:

1) The length of the brake pedal lever, a longer lever means a greater multiplication of force

2) The multiplier effect ratio of the brake booster if present ("power brake effect").

3) The ratio of the areas of the master cylinder piston and caliper pistons

4) Any offsets in system pressure from the antilock braking system (ABS) or from air in the brake fluid.

Of the above, 1 and 2 produce the system hydraulic pressure. The size of the caliper pistons used in relation to the system hydraulic pressure controls the clamping pressure applied to the pads at the caliper and thus the brake torque at that wheel. *The larger the caliper piston area relative to the master cylinder piston area the greater the clamping force and the greater the brake torque produced.*

Thus, different sizing of the caliper pistons in the front and rear calipers is one parameter used in brake system design to control distribution of brake torque front to rear. This is the static "brake bias" of the system and as we will see can be subject to dynamic change during braking.

The coefficient of friction of the pad material is sometimes used in brake tuning and design to achieve a different distribution of front to rear brake torque. A less "sticky" low coefficient pad will lower the brake torque. Manufacturers of pad material describe the coefficient of friction as the Greek letter μ. Most Porsches use the same pad material and hence the same μ front and rear, however some do not, Porsche specifies a different pad material front and rear in some Turbo applications for example.

As noted above, unlike tire rubber, brake pad materials in general are not very pressure sensitive and μ does not tend to change with pressure. A larger pad only distributes the contact pressure over a larger area and μ does not change significantly at the lower surface loading, so pad size is not used to change brake torque.

Brake torque will be essentially the same, if the pad temperature is the same, despite a larger pad.

The diameter of the disc is used to control brake torque, a larger diameter disc will produce a greater brake torque.

Thus, different sizing of the brake disc is another parameter controlled in brake design to control front to rear brake torque distribution.

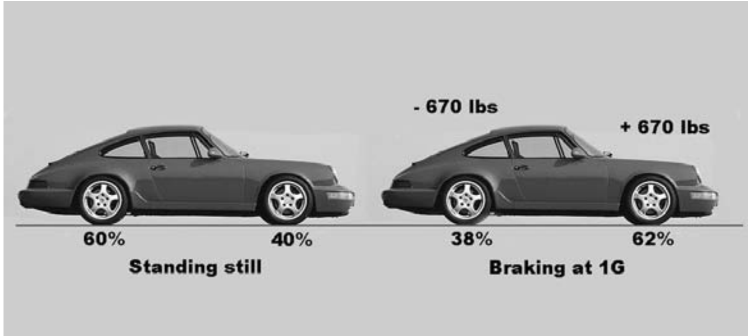
Also, *larger discs offer more surface area for heat dissipation* and for these reasons discs are larger diameter (and usually thicker) at the front of the car.

So as we can see the brake system designer has many ways to control brake torque. The other side of the brake couple marriage, wheel torque is not so easy to control.

Load on the Tire Contact Patch: a Constantly Changing Variable

The tire load and hence wheel torque that can be generated is dependent on the basic layout of the chassis' wheelbase and center of gravity and how fast the car is decelerating. Isaac Newton steps in during the stop and continuously changes weight distribution for us depending on how hard we are trying to stop the car.

Let's look at the weight on the contact patches of a 911 Porsche's tires and how things change during braking. A parked Porsche 911 has roughly 40% on the front wheels and 60% of its weight on the rear wheels. This means that a parked, 3000 pound 911 would have a 1200 pound load on its front tires and an 1800 pound load on its rear tires. This changes when the car is braked though, *deceleration causes weight on the front tires to increase and the weight on the rear tires to decrease*. This is a zero sum effect; weight added to the front is subtracted from the rear. This effect is called forward weight transfer and the amount that occurs is a function of the wheelbase length (L) and the height of the center of gravity (CG) and deceleration rate in "G" or units of gravity and total weight of the vehicle. In effect, the CG height acts as a lever perpendicular to the wheelbase lever, transferring weight forward. Think of sitting in a 4 legged dining chair and getting a push from behind, load is shifted to the front legs of the chair and subtracted from the rear legs of the chair.



Let's assume that a 911 has a 20 inch high center of gravity and an 89.5 inch wheelbase and undergoes a stop equal to 1 "G" (the car is stopping as hard as gravity is holding it to the ground). This would mean: (20" CG/89.5" L) X 3000 pounds X 1 G = 670 pounds of weight transfer occurs from the back of the car to the front of the car. The 40% front, 60% rear distribution has shifted to 62.3% front and 37.7% rear.

A complete reversal from the static parked condition weight distribution occurs during maximum braking!

The balance of front to rear braking required, the so called: "Brake Bias" is very important and it changes dependent on how fast the car is stopping.

To compensate for this forward weight transfer during maximum brake effort the brake system designer can incorporate a pressure limiting valve between the master cylinder and the rear brakes. This valve starts to limit pressure to the rear brakes once a preset pressure in the valve is reached. This means that in less-than-maximum braking, the pressure in the front and rear brake systems is the same. However, as you push harder on the brake pedal, brake fluid pressure increases to a pre-selected pressure point, where further increases to the rear brakes will be limited.

This is very important because we do not want the rear brakes to lock up the tires before the front.

If the rear brakes lock up first, dynamic stability of the chassis is lost, since control is limited with a sliding tire. The car becomes relatively like an arrow without its stabilizing feathers and tries to fly backwards. Also, if brakes are applied while the car is turning into a corner, so called "trail braking" becomes much more difficult with relative increases in rear brake bias.

Since the wheelbase is essentially fixed, the only aspect of chassis design affecting brake bias that is easily controlled is height of the center of gravity, which can be adjusted fairly easily. Lowering the car 2.5 inches as Porsche did in the Carrera Cup racing cars would decrease the load transfer from 670 to 587 pounds, a 14% change.

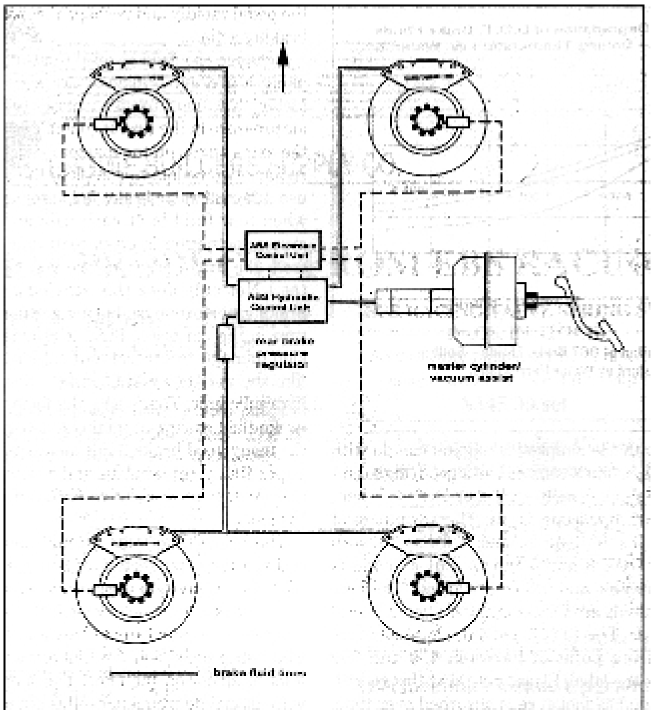
The lower the car is, the lesser the weight transfer to the front wheels and the higher the set point of the proportioning valve can be, or the valve can be eliminated altogether.

Furthermore, when a car's center of gravity is lowered, less load is transferred from the rear tires to the front tires, the sum of the four tires coefficient of friction rises, and the car will stop faster.

So as we can see, the most important elements in the design of the brakes is brake torque distribution relative to wheel loads and overall sizing of the components to dissipate heat.

Once the system is designed to optimally distribute brake torque relative to wheel torque it is up to the driver to sense the point of impending wheel lock up so as not to slide the wheels.

Remember that coefficient of friction we talked about, we want to maximize that during the stop and sliding the tires defeats this purpose.



For this reason Porsche introduced antilock braking systems (ABS) on their cars. ABS is a wonderful computer age device that magically allows the driver to find the coefficient of friction sweet spot by just mashing the brake pedal as hard as they can. Only a little finesse required. This is done by a microprocessor which continuously keeps track of wheel speeds and compares their relative changes to one another. Early systems use a design which compares each front wheel and the pair of rear wheels together in a 3 channel design, the later system in later cars compares all wheels individually in a 4 channel design. When a wheel changes speed downward at a rate deemed implausible by the computer, brake line pressure to that wheel is pulsed until wheel speed increases again, preventing sliding. The trick is programming the computer to reliably find the maximum coefficient of friction and there have been programming improvements in the later Bosch systems to do this. There are drivers whose skills still out match ABS at threshold braking, but they are fewer in number.

If the brakes have enough brake torque capacity to counter wheel torque, and the system is well designed to distribute brake force, the car will stop no faster and therefore:

Adding larger brakes will not necessarily stop the car faster.

This is an important point, since a well maintained Porsche will probably stop no faster with larger brakes, since the brakes are plenty adequate to lock up the wheels already, at least for several stops made sequentially from high speed.

The only way to make your Porsche stop faster is to lower the car and/or fit higher coefficient of friction tires/ large contact patch tires, not simply larger brakes.

This point may be particularly applicable to autocross where adding the rotating, un-sprung weight of a larger brake system is usually of no advantage.

Having said the above, larger brake systems tend to have more rigid calipers and due to the larger diameter discs operate at a lower system pressure providing better brake feel, allowing the driver to control braking easier.

In summary, we've covered the components that affect brake torque and wheel torque, and shown how the brake designer takes the different considerations for each of the components into account in developing the braking system. Readers desiring additional information should see references 6 and 7. Next month in Part 2, we'll look at the components of the 964 braking system that put these principles into play, their specifications, and 964 brake modifications.

In Part 1 of this article (Panorama, June 2005), we reviewed the components that affect brake torque and wheel torque, and discussed how the brake designer takes the different considerations into account. In this month's Part 2, using the 964 model, we'll discuss the application of those principles, and upgrades/modifications.

Brake Background

Up until the late 1970's, Porsche production disc brake systems generally consisted of two piston brake calipers, manufactured by ATE, which continued to be used through 1989. When improved braking was called for, Porsche switched to four piston calipers, with better piston application against larger brake pads. Sourced directly from the 917 racing program, four piston calipers were first used in production on the 1974 Carrera RS 3.0. Next, the 930 Turbo brakes, introduced in 1978, were designed and manufactured by Porsche, based on the 917 brakes.

In the mid-1980's, Brembo was called upon for a partnership as supplier of calipers to Porsche. With three brake pad sizes, Brembo provided these four piston calipers, with different piston sizes, through 1998: the smaller of the calipers, introduced on the 1985 944 Turbo, the medium S4 caliper introduced on the1986 Porsche 928 S4, and the large "Big Black" calipers introduced on the 1992 928 GTS (also used in red color for 911 Turbo applications). The calipers use two sizes of pistons in each caliper half, which reduces taper, or uneven brake pad wear, that can occur when equal piston sizes are used.

From the start, the 964 has used different combinations of Brembo calipers at the front and rear of the car. Starting in 1989, the C4 used the Brembo small 4 piston calipers, with different piston sizes, in the front and rear. Paul Frere said "Judging by contemporary test reports, this was probably the best braking system of any contemporary car" (Reference 1). In 1990 and 1991 the C2 was produced with the small 4 piston caliper on the front, but with a smaller two piston Brembo rear caliper. In 1992, the rear two piston caliper was replaced with the four piston rear caliper used on the C4. The Carrera RS and Turbo 3.3 use medium S4 calipers in front and small calipers in the rear, while the Turbo 3.6 carries Big Reds in front and medium S4 calipers in back. Note the medium S4 black calipers used on the front of the 993 C2 and the Carrera RS/Turbo 3.3 are different castings, to work with their respective 304mm and 322mm discs.

964 braking system components and their characteristics

Components	Characteristics
Vacuum/Hydraulic booster	System pressure
Master cylinder	System pressure
Bias valve	Front to rear brake bias
Caliper	Brake torque distribution with clamping force change

Disc	Brake torque distribution with diameter change Heat dissipation potential
Pads	Brake torque tuning with coefficient of friction (μ)

On 964's, Porsche uses two systems to assist transferring motion at the brake pedal to the calipers. On the C4, the electronic front and rear differentials use a high pressure (up to 2,600 PSI) electro-hydraulic system, which is also used as the pressure source for the brake boost system. This electro-hydraulic boost system is also used on the 964 Carrera RS and 964 Turbo. The C2 uses a more conventional vacuum-based boost, with the vacuum canister occupying the C4's front differential location.

The 964 uses one of three master cylinders sizes: 25.4mm for the Carrera RS, 23.81mm for the C4 and Turbo, and 20.64mm for the C2. The RS/C4/Turbo electro-hydraulic boost master cylinder is not interchangeable with the C2 vacuum boost master cylinder.

	Bar	Part Number
964 C2 to 1991	45	964.355.305.00
964 C2 1992+	55	964.355.305.10
964 C4	55	964.355.305.10
964 Carrera RS	55	964.355.305.10
964 Turbo, Turbo 3.6	60	965.355.305.01

Note 1 bar equals 14.5 PSI

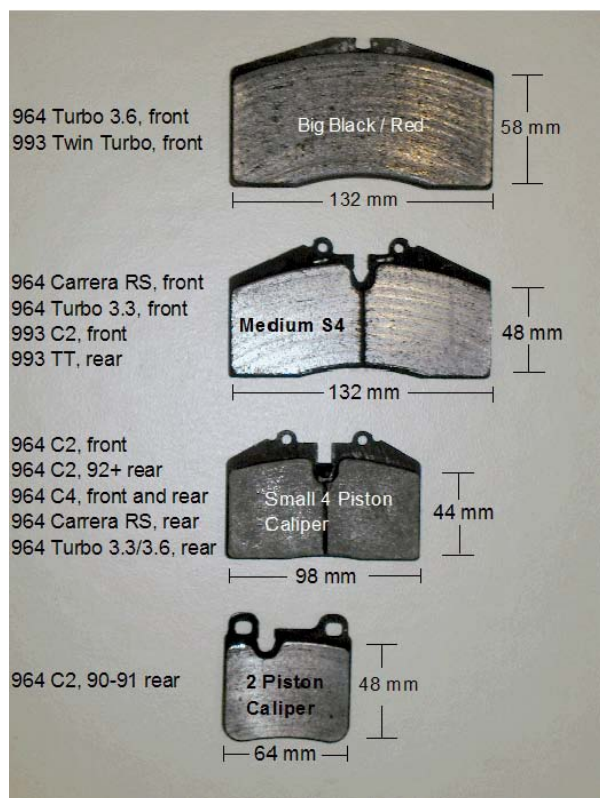
Table 1: Bias valves

In order to prevent the rear brakes from locking up before the front brakes, 3 different bias, or pressure limiting, valves are used, which are shown in table 1.

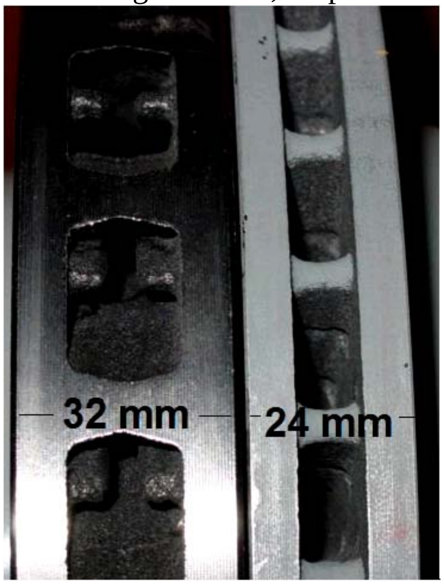
All 964's have antilock braking systems, to control wheel lockup. Discussion can be found in references 1 and 3.

Brake fluid can also play a role in the system pressure in the braking system. Brake fluid is hygroscopic, meaning over time it can absorb water, which reduces it's boiling point. When brake fluid is boiled, air bubbles are generated which compress at a very different rate than the brake fluid. This is characterized by the pedal going to the floor towards the end of a track day. That's why it's critical, when driving on the track, to change brake fluid more frequently than the factory recommended 2 year intervals. Some people change their fluid before each track event.

In figure 3, the four sizes of brake pads are shown, along with measurements and application, including upgrades. Recall that larger pads, by themselves, don't change the braking balance. However the pistons used in the calipers that accommodate larger pads are larger, which generates greater clamping forces, which changes the brake balance.



Vented discs, which have two disc faces with vanes in between them for additional cooling, are used for the 964 front and rear discs. The discs used on the stock C2/C4 have radial cooling vents similar to those first introduced by Porsche for the 1967 911 S model. Since the development of vented discs, Porsche has improved on the venting by curving the internal vanes, and adding half fins, to produce a pumping action of air through the disc to improve cooling (which Porsche also patented) (Reference 2). In addition, adding holes into the disc surface was discovered in attempts to lighten the 917 racing car. The holes not only lighten the disc, but improve braking by clearing gases generated by the pads, as well as removing rain water, from the disc surface. These types of discs have been referred to by Porsche as cross-bored or cross-drilled, and are generally called 'drilled' discs. However, Porsche discs aren't drilled, but have the holes cast in place during manufacturing, which aides disc longevity. Figure 4 compares a 24mm wide stock rear disc, with radial vanes, with a 32mm wide disc. Note the wider disc's curved cooling vanes, as well as a wider air gap, to enhance cooling. You'll see in table 1 and 2 that curved cooling vane discs have different part numbers for the left and right side, unlike radial vane discs, where one disc works on either side. When taking curved vane discs off, consider labeling them to ensure they go back on the correct side.



A summary of 964 calipers and discs, with two popular upgrades, is shown in table 2 (front) and table 3 (rear):

Model		Front Caliper	Piston Size (mm)	Front Disc	Front Disc Size (mm)	Front Disc Type
964 C2 to 1991	L	964.351.421.02	40/36	964.351.041.02	298x28	Solid/Vented
	R	964.351.422.02	40/36	964.351.041.02	298x28	Solid/Vented
964 C2 1992+	L	964.351.421.02	40/36	964.351.041.02	298x28	Solid/Vented
	R	964.351.422.02	40/36	964.351.041.02	298x28	Solid/Vented
964 C4	L	964.351.421.02	40/36	964.351.041.02	298x28	Solid/Vented
	R	964.351.422.02	40/36	964.351.041.02	298x28	Solid/Vented
964 Carrera RS	L	965.351.423.01	44/36	965.351.043.00	322x32	Cross-drilled
	R	965.351.424.01	44/36	965.351.044.00	322x32	Cross-drilled
964 Turbo	L	965.351.423.01	44/36	965.351.043.00	322x32	Cross-drilled
	R	965.351.424.01	44/36	965.351.044.00	322x32	Cross-drilled
964 Turbo 3.6	L	993.351.425.10	44/36	965.351.045.00	322x32	Cross-drilled
	R	993.351.426.10	44/36	965.351.046.00	322x32	Cross-drilled
993 brake upgrade	L	993.351.421.00	44/36	965.351.041.01	304x32	Cross-drilled
(requires caliper adaptors)	L			928.351.043.60	304x32	Solid/Vented
	R	993.351.422.00	44/36	965.351.042.02	304x32	Cross-drilled
	R			928.351.042.02	304x32	Solid/Vented
'Big Red' upgrade	L	993.351.425.10	44/36	965.351.045.00	322x32	Cross-drilled
(requires caliper adaptors)	R	993.351.426.10	44/36	965.351.046.00	322x32	Cross-drilled

Table 2: Front calipers and discs

Model		Rear Caliper	Piston Size (mm)	Rear Rotor	Rear Disc Size (mm)	Rear Disc Type
964 C2 to 1991	L	964.352.425.03/05	44	951.352.041.02	299x24	Solid/Vented
	R	964.352.426.03/05	44	951.352.041.02	299x24	Solid/Vented
964 C2 1992+	L	928.352.421.03	30/28	964.352.041.02	299x24	Solid/Vented
	R	928.352.422.03	30/28	964.352.041.02	299x24	Solid/Vented
964 C4	L	928.352.421.03	30/28	964.352.041.02	299x24	Solid/Vented
	R	928.352.422.03	30/28	964.352.041.02	299x24	Solid/Vented
964 Carrera RS	L	993.352.421.00	34/30	951.352.041.91	299x24	Cross-drilled
	R	993.352.422.00	34/30	951.352.041.91	299x24	Cross-drilled
964 Turbo	L	965.352.421.02	34/30	965.352.041.00	299x28	Cross-drilled
	R	965.352.422.02	34/30	965.352.042.00	299x28	Cross-drilled
964 Turbo 3.6	L	965.352.421.12	34/30	965.352.041.00	299x28	Cross-drilled
	R	965.352.422.12	34/30	965.352.042.00	299x28	Cross-drilled
993 brake upgrade	L	993.352.421.00	34/30	951.352.041.91	299x24	Cross-drilled
	L			964.352.041.02	299x24	Solid/Vented
	R	993.352.422.00	34/30	951.352.041.91	299x24	Cross-drilled
	R			964.352.041.02	299x24	Solid/Vented
'Big Red' upgrade	L	965.352.421.12	36/30	951.352.041.91	299x24	Cross-drilled
(requires caliper modification)	R	965.352.422.12	36/30	951.352.041.91	299x24	Cross-drilled

Table 3: Rear calipers and discs

Modifications

Basic 964 brake topics (pads, fluid, cooling) are covered in reference 4. As stated earlier, 964 brakes, for street usage, are very good as they come from the factory. If your existing brake setup, with fresh brake fluid and with all components in good condition, can engage your antilock brakes, a brake upgrade won't help you stop any faster. There are really only two reasons to modify your braking system; to gain more heat sink capabilities from larger diameter/width discs or because you like the looks of Big Red/black calipers and discs with holes. The strategy to improve the stock brake system is twofold, first, to incorporate the larger diameter, wider, curved vane discs, with or without holes, for greater braking efficiency. Second, to use larger calipers, which tend to run cooler, and larger pads which last longer and also run cooler. An important consideration in making any of the updates described below, is to ensure whoever makes the updates is qualified and competent to safely complete and test them. Obviously, since the authors are not doing the work, they can't guarantee or take responsibility for the fitness or success of modifications to your 964.

Here are the Porsche parts-based 964 brake system upgrades, with the benefits of each:

<u>Upgrade to 4 Piston Rear Calipers For 1990-1991 C2</u>

- 964 small 4 piston rear caliper
- 55 bar bias valve

By upgrading the rear brake calipers and bias valve, this brings the 1990-1991 964 C2 to the same specification as the 1992+ 964 C2's and all 964 C4's. This should be considered a necessary upgrade for track usage, for more balanced high speed braking, as well as a larger pad for improved durability and fade resistance. *Note: Do not make the mistake of fitting the front calipers to the rear. While the parts bolt up, the front caliper pistons are much larger than the rears, and too much brake torque in the rear will result in unstable braking.*

<u>Upgrade to 993 Brakes</u>

- 993 medium size 4 piston calipers (requires caliper adaptors)
- 304 X 32 mm front discs, using either solid/vented 1986-1991 928 S4 or cross-drilled 968 M030 discs. A 993 front disc has the wrong offset for a 964.
- Optional 964 Carrera RS cross-drilled rear discs, if desired to match front cross-drilled discs
- 993/964 Carrera RS four piston rear calipers (they are the same caliper)
- Recommended: 993 master cylinder for C2
- 60 bar Turbo bias valve

This upgrade enhances brake cooling by fitting a larger diameter, thicker disc with curved internal vanes for improved cooling. The front caliper is larger than the rear caliper, and uses a larger pad for improved durability and fade resistance in track use. This is an attractive upgrade if you have sixteen inch wheels, which can still fit over the 993 calipers; however, a small spacer is required for the front wheels (a 1/8" or 3mm spacer works with 16" Cup 1 wheels).

<u>Upgrade to Carrera RS/Turbo 3.3 Brakes</u>

- 964 Carrera RS/Turbo 3.3 medium 4 piston front calipers (requires caliper adaptor)
- 322 X 32mm cross-drilled front discs from Carrera RS or 3.3 964 Turbo
- 993/964 Carrera RS rear calipers (they are the same caliper)
- 964 Carrera RS cross drilled rear discs
- Recommended: 993 master cylinder for C2. For track use, RS upgrade for C4, Turbo
- 60 bar Turbo bias valve

This upgrade further enhances brake cooling with a larger disc. By themselves, the front calipers would increase front brake bias, however, this is balanced by fitting the 993 calipers with larger pistons in the rear. Discs now have holes and curved, directional, vanes in the front. This upgrade requires 17 inch wheels.

<u>Upgrade to Red Caliper Turbo 3.6 Brakes</u>

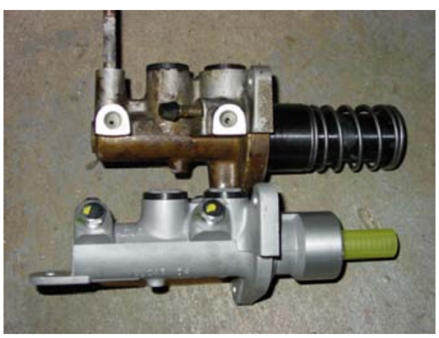
- Turbo 3.6 large 4 piston front red calipers (requires caliper adaptor)
- 322 X 32mm cross-drilled front discs from 3.6 Turbo
- Red 3.6 Turbo rear calipers modified by VCI (www.vehiclecraft.com) for use with 24mm non-turbo disc, or powder coat red 993 rear calipers (reference 5). Since the Turbo 3.6 calipers are designed for 28mm discs, using them, unmodified, with 24mm discs can result in brake failure, should the pads fall out, and is not recommended. Turbo discs have the wrong offset for non-Turbo 964's.
- 964 Carrera RS cross-drilled rear discs
- Recommended: 993 master cylinder for C2. For track use, RS upgrade for C4, Turbo
- 60 bar Turbo bias valve

The main advantage of this system over the Carrera RS/Turbo 3.3 upgrade is a larger front pad and a front disc with more swept area. Disc is also slightly heavier for more thermal mass. Has the RED color people love. Note the required adaptor in figure 5. This upgrade requires 17 inch wheels, and depending on the wheel, might require 18" wheels.

Upgrade to Large Black Caliper 928 GTS Brakes

- 928 GTS large 4 piston front black calipers (requires caliper adaptor and crossover pipe/brake bleeder interchange)
- 322 X 32mm cross-drilled front discs from 3.6 Turbo
- 993/964 Carrera RS four piston rear calipers (they are the same caliper)
- 964 Carrera RS cross-drilled rear discs
- Recommended: 993 master cylinder for C2. For track use, RS upgrade for C4, Turbo
- 60 bar Turbo bias valve

Did we mention that both the 928 and 993 caliper color is black, like the original 964 calipers? This is the Q-ship upgrade, which is functionally the same as the Big Red upgrade, however, it uses black 928 GTS front calipers and black 993 rear calipers. The 928 calipers require that the crossover pipes and brake bleeders be flipped top to bottom, otherwise the piston size relative to wheel rotation will be incorrect for the 911 application. This is because the 928 calipers are mounted on the trailing edge of the disc, while 911 calipers are mounted on the leading edge of the disc. An advantage of this upgrade is that the rear calipers do not need to be machined since they are designed for the 24mm disc. This upgrade requires 17 inch wheels, and depending on the wheel, might require 18" wheels.



Some people notice when upgrading to larger brakes that the brake pedal travels a bit further after the upgrade. For most, this isn't a problem. However, when used with the larger calipers, it's possible that the 964 master cylinder won't have the reserve capacity to deal with air in the brake fluid or boiling brake fluid. To address this, installation of a larger master cylinder is recommended when installing larger piston calipers. Here we'll describe the master cylinder upgrade to the 23.81mm 993 C2 master cylinder. A 993 master cylinder, shown below a 964 C2 master cylinder in figure 6, requires a new vacuum canister, as Porsche moved the return spring previously on the master cylinder, into the vacuum canister. The minimum parts required are listed in table 4.

Master Cylinder	993.355.910.00
Vacuum cannister	993.355.023.10
Gasket	993.355.301.00
MC support	993.355.163.03

Table 4: 993 Master Cylinder Upgrade Parts

While you're in there, check the reverse lever bearings, shown in figure 7, that are coated with a teflon-like material, and renew if needed (the reverse lever enables the ninety degree turn from the brake pedal rod to the vacuum canister and master cylinder).

In addition, you have to address the 12mm fittings on the 993 master cylinder versus the 10mm fittings on the 964 master cylinder. There is a 12mm to 10mm adaptor made by Weatherhead, however, the 10mm side requires an inverted flare tube ending, as opposed to the bubble flare ending Europeans use. Not difficult to do with the right flaring equipment. Another option is to have your stock lines duplicated with the proper fittings. Classic Tube, (www.classictube.com), can do that for around $35/pair. You send in your existing lines, to be replicated with new 12mm/10mm fittings. Have them make the master cylinder end, with the 12mm fitting, an inch longer, to accommodate fitment into the 993 master cylinder. When you receive the lines, you'll need to curve the end of each line to fit into the master cylinder, using one of the available brake tube bending tools.

Fitting the larger 993 vacuum canister can be a challenge. As you can see in figure 8, the 993 vacuum canister on the left is slightly larger than the 964 vacuum canister on the right. Depending on the size of your front sway bar, you may need to ensure the sway bar is mounted as far forward as possible. With RS sway bar mounts for the Porsche 24mm adjustable bar, you should be using 3/8" (9.5mm) bolts. A washer may be required between the vacuum canister aluminum mount and frame, to slightly angle the vacuum cannister off the sway bar. Ensure the plastic brake reservoir to master cylinder lines aren't rubbing on the 993 vacuum cannister center edge. When it's all hooked up, you may need to adjust the brake pedal so it's even with the clutch pedal.

Knowing that rubber brake lines should be replaced every 10 or so years, if you don't know when yours were last replaced, a major brake upgrade is a great time to replace them.

Of course, if all you want are red, or non-black colored calipers, there are special caliper paint kits available, and you can buy the 'Porsche' brake decals in various colors, too. Another approach is to powder coating your calipers red (reference 5).

In closing, we've covered braking system basics, and shown how they are addressed in the 964 family. We've also discussed some upgrades that can be made. Remember that your brakes are a critical component of your Porsche. One of the best measures you can take to keep your brakes in top notch condition is to change your brake fluid regularly.

Thanks to Joel Reiser for his helpful draft review, and to Jeff Curtis for pictures.

Reference:

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(4) 964 Track Preparation, by Bill Gregory, *Porsche Panorama*, March 2004, p. 36
(5) How to do Red Calipers, in the DIY section at www.p-car.com
(6) *Brake Handbook*, by Fred Puhn
(7) *The Racing & High Performance Tire*, by Paul Haney