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TECHNICAL WHITEPAPER:

Brake Pedal Setup & Dual Master Cylinder Installation Guide

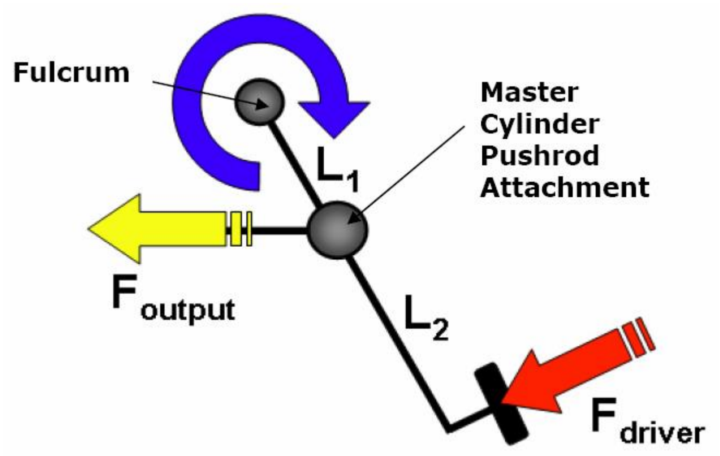
Overview

The conversion of a brake system from a typical, factory-supplied, vacuum-boosted (vacuum assisted) tandem master cylinder to a racing-style dual master cylinder requires that the assisting force originally provided by the booster be replaced by an increase in the mechanical leverage in the pedal assembly and/or an increase in the piston area differential between the master cylinder (connected to the pedal lever) and the brake caliper piston or pistons.

If all the assisted force were made up by mechanical leverage in the pedal assembly it is likely that the pedal throw would be too long before substantial brake work would begin. If the pedal ratio is less than required to generate the required force, then either the master cylinder diameter will have to be reduced or the brake caliper piston sizes will have to be increased to put in place a hydraulic system ratio advantage to make up the difference. A combination of all three is usually employed to compensate for lack of assisting force.

Brake Pedal Design and Selection

First, let's define the term pedal ratio. The pedal ratio is the overall pedal length or distance from the pedal pivot called the fulcrum to center of the pad your foot will push against (L1+L2) divided by the distance from to the fulcrum to the master cylinder push rod attachment point (L1).



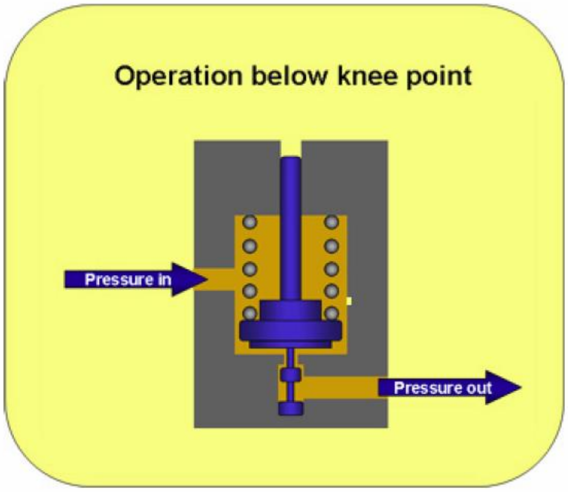
Experience has shown that a pedal ratio of 6.2:1 is recommended (with 5.5:1 being the recommended minimum) to replace most of the brake force assist that was provided originally by the vacuum assist and the original equipment pedal ratio of 3.5 to 4.0:1. This means that you cannot usually reuse the original equipment pedal to build a pedal arrangement with dual master cylinders because the stock pedal is simply not long enough and often the fulcrum is too low to the floor to provide enough room to make the brake pedal longer.

Shortening the distance from the fulcrum to the pushrod would have the same effect, but is a difficult task best left to an expert fabricator. Without this extra mechanical advantage, you would have to use a smaller master cylinder than may be available or you are at least setting yourself up for a difficult time in picking other system components to make up for the missing mechanical advantage. There are many well-designed and manufactured pedal arrangements with dual master cylinders available from race component suppliers. If you still choose to fabricate your own assembly then take care to design and build a sound pedal.

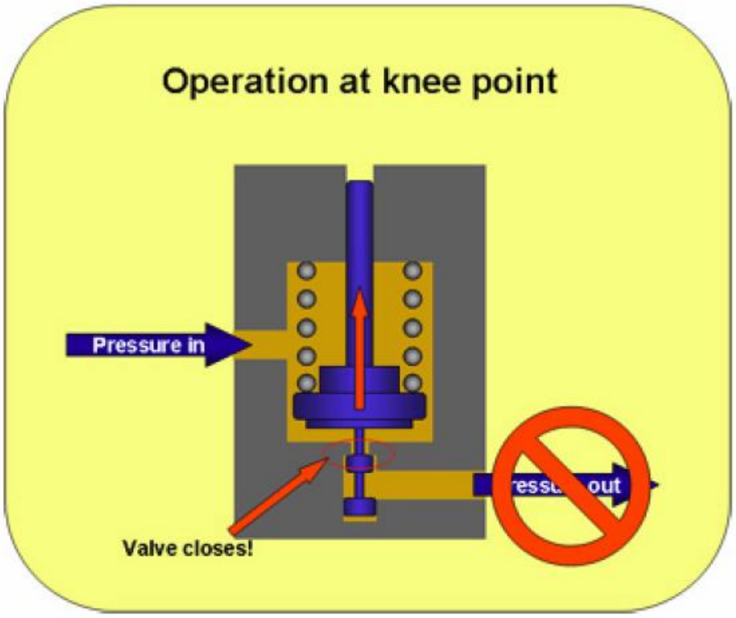
Balance Considerations

A common mistake is to undersize the rear circuit pressure or caliper piston size causing an incurable front bias. Starting out with a slightly greater rear bias will give you options to set the balance to the desired level. The rear bias can be resolved by resetting the balance in the dual master cylinder array more to the front (using the balance bar) or, in the case of a tandem master cylinder, using what is commonly referred to as a brake-proportioning valve.

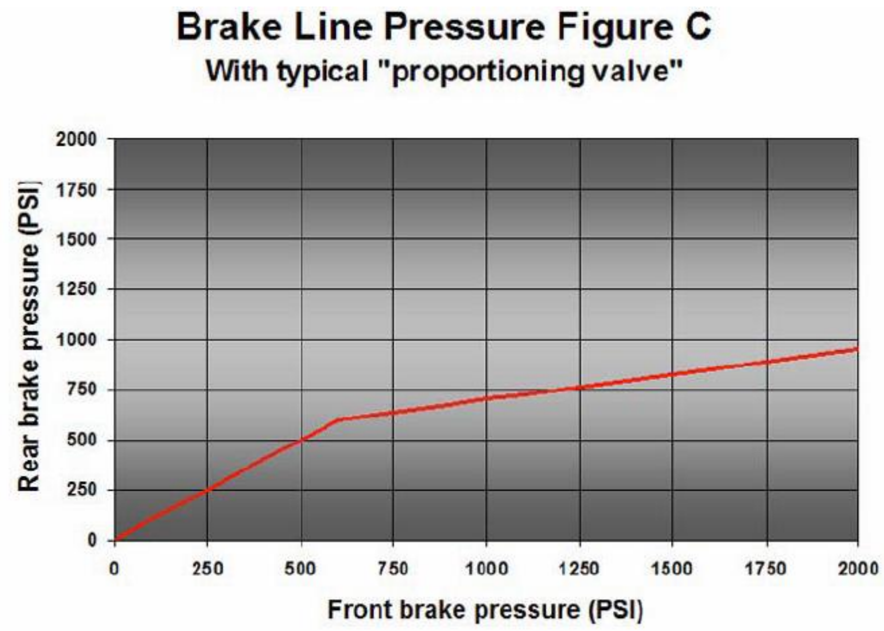
The name brake proportioning valve is misleading and seems to imply a change in the ratio of force between the front and rear circuits. This is, in fact, not the case – the valve is actually a pressure-regulating device. As you change the screw or cam adjustment on the valve, a preloaded spring is relaxed or compressed, pushing against a piston that is schematically connected in a tee or in parallel or as shown below in a more elaborate arrangement.



When the pressure in the circuit that the valve is connected to reaches a point where the resultant force exerted by the piston matches the spring preload, the piston lifts off of its seat and acts like an accumulator or a control valve as shown.



Any further increase in pressure is at a rate that equals the (relatively low) spring rate. On a graph showing pressure plotted against pedal force in the circuit that the valve is installed in, you will see a linear rise or slope up to the preset pressure (knee point) and then a sharp transition to a different slower rise rate or slope.



Due to the design of this valve, it should never be used on the front circuit because force output on the front should always directly respond to driver input without any limitation.

If too much mechanical advantage exists over the front brakes (in other words the front brakes are too easy to lock up), then one should consider resizing the brake caliper piston size(s) downward to reduce force output or, in the case of dual master cylinders, resize the front master cylinder piston size upward.

In the case that you must use a tandem master cylinder with a stock-like pedal arrangement for whatever reason, make sure that your selected master cylinder and the brake caliper piston sizes for both the front and rear circuits are correct. You will have less than the best possible brake performance by depending on proportioning valves discussed to correct for the wrong brake system component sizes being used. These valves are best used at or near their maximum installed spring preload on cars with tandem master cylinders with a full load of fuel (presuming the fuel is carried in the back) and on a wet track because the balance will be more biased to the rear under wet conditions due to lower weight transfer.

Master Cylinder Selection

In general, if you have a pedal ratio of approximately 6.2:1 then it is likely that a 3/4 inch (0.750 inch or 19 mm) master cylinder will be close to the right size when combined with a front 4-piston caliper with piston sizes of 38mm and 42mm and a tire with a 24.4 inch outer diameter (such as a commonly used tire size 245/40R17).

It is possible to calculate the master cylinder sizes with relative precision, but you will need the following data, in either metric or English units:

1. Static weight on front axle
2. Static weight on the rear axle
3. Maximum deceleration rate expected (typically between 1.0 to 1.5g for sedan or sports cars, unitless)
4. Center of gravity height (go online to learn methods of determining using corner weight scales)
5. Wheelbase
6. Tire rolling diameter (you can use the tire diameter)
7. Brake caliper piston sizes front and rear, converted to total piston area (piston area = diameter of each piston squared, then divided by 4, then multiplied by π, or 3.142)

8. Effective radius of the brakes front and rear, or the lever over which the pads apply their clamping force (approximately ½ of the rotor radius minus ½ of the average piston diameter will be relatively close)
9. Pad friction coefficient, front and rear (if you do not know, assume it is 0.5 for race friction and 0.4 for street friction, also unitless)
10. Pedal ratio (as discussed previously)
11. Target driver foot effort at maximum brake output. For racing use this should be around 80 lbs. We are actually speaking of force here so we should use the correct convention and call it pound-force written as lbf. One lb by definition is equal to one lbf in the earth's gravitational field of one G. One lbf also equals 4.448 newtons (N) and 0.454 kgf. The same convention of mass versus mass in a gravitational field applies between kg and kgf. The reason for making this point will be made clear later in the context of driver leg input effort.

In all cases the result of the calculations below will need to be tested since the vehicle behavior under braking is also affected by suspension design and set up, tire pressures, shock set up and spring used.

To begin the calculation, we need to estimate the weight transfer under a maximum deceleration or –G stopping force scenario. Start by adding the Static Front and Rear Weight (1 and 2 above):

12. Vehicle mass (or total weight) = M = Static Front + Rear Weight

To calculate weight transferred (ΔW), multiply M by the maximum deceleration rate (3 above) multiplied by Center of gravity height (4 above) divided by Wheelbase (5 above):

13. ΔW = M * γ (rate of deceleration in negative Gs) * Ht of C.G. / Wheel base

ΔW is then added to the static front weight and subtracted from the static rear weight for the purpose of estimating the dynamic axle loading conditions:

14. The Dynamic Front Axle Weight during a maximum -G stop = Static Front Weight + ΔW

15. The Dynamic Rear Axle Weight during a maximum –G stop is = the Static Rear Weight – ΔW

Next, we need to calculate the maximum individual front and rear torque requirement by dividing the dynamic weight in half and multiplied by half the rolling diameter of the tire (6 above) and multiplied by Maximum Deceleration Rate (3 above):

16. Torque front = T_{front} (units are either lb-ft or N-m) = (Dynamic front axle weight in either pounds or newtons / 2) * (Tire Rolling Diameter front in feet or meters / 2) * Maximum deceleration rate

17. Torque rear = T_{rear} (units are either lb-ft or N-m) = (Dynamic rear axle weight in either lbs or newtons / 2) * (Tire Rolling Diameter rear in feet or meters / 2) * Maximum deceleration rate

The torque output of the front and rear brake system will have to equal these values for a stopping event at maximum deceleration.

The torque output for the front brakes can be expressed as follows:

18. T_{front} = A_{pfront}, total Area of pistons for one half of front caliper or in the case of a slider caliper design the total area of pistons of front caliper (7 above) * R_{front}, the effective radius for the front brakes (8 above) * μ, the pad friction coefficient (9 above) * 2 (for two sides to the rotor and pad interfaces) * P_f, the circuit pressure

Now we want to change the equation to solve for the front circuit pressure:

19. Front circuit pressure = P_{front} (in N/mm^2 or psi) = T_{front} (from immediately above) /A_{pfront} / R_{front} / μ_{front} / 2 (don't forget the 2)

Similarly, we can solve for the rear by substituting the data that is different for the rear:

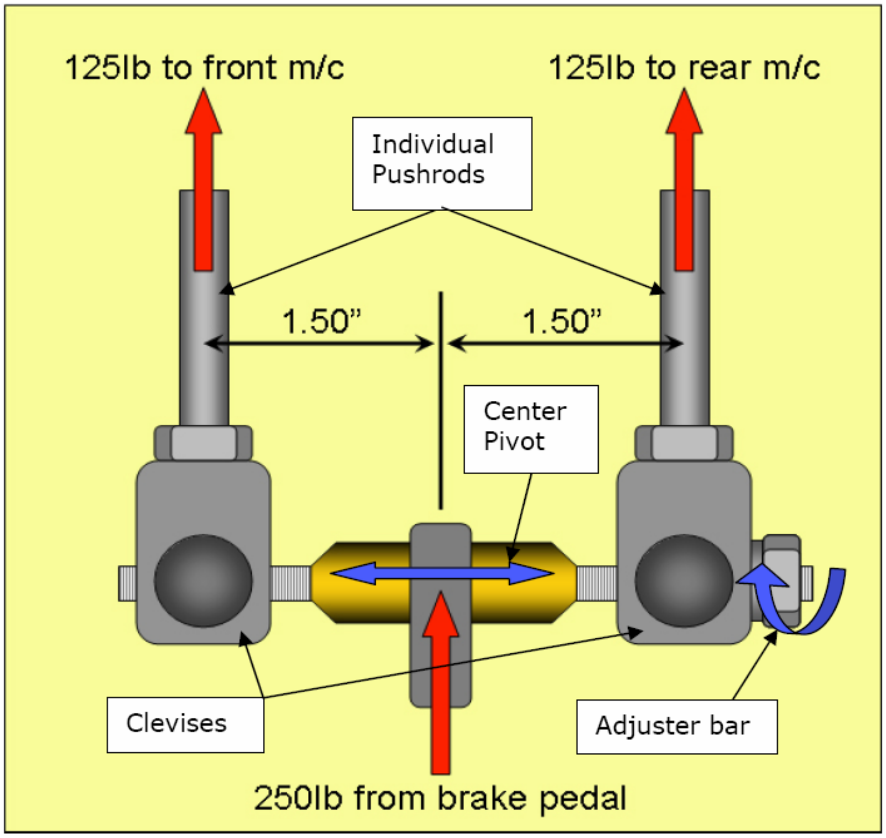
20. Rear circuit pressure = P_{rear} (in N/mm^2 or psi) = T_{rear} (from immediately above) /A_{prear} / R_{rear} / μ_{rear} (rear specific, if different) / 2 (don't forget the 2)

With the circuit pressure requirement known one can solve for the pedal ratio and master cylinder size. U.S. Federal and E.C. regulations for automobile and light truck braking performance establish requirements for maximum effort by a driver in the case that the brake assist fails. In some cases the assisted effort is too low and the unassisted effort might be close to what a race driver would want. Typically on a street car effort is at or below 40 lbs (~178 N or 18 kgf). In high performance vehicles and race cars we try to keep the leg force required below 120 lbs (~534 N or 54 kgf). Eighty lbs (~356 N or 36 kgf) is ideal for most race applications. We provide the kgf unit of mass conversion at one G so that readers used to using metric units can make a comparison of the data being presented to one half of their body mass being the force they experience on each of their feet while standing due to gravity.

To determine master cylinder pushrod input force:

21. Master cylinder pushrod input force = Driver foot input force / 2, since this force will be distributed to two master cylinders and presuming for calculation purposes that the pedal bias adjuster will be centered * pedal ratio

For example, 40 pounds of driver input force with a 6.2:1 pedal ratio results in 250 lbs of input pedal force to the adjuster bar and 125 lbs of master cylinder input force acting on each master cylinder pushrod with the bar centered.



If we subsequently determine that we need to change the bias, we will turn the adjuster bar screw causing the center pivot to move closer to one of the master cylinders. The master cylinder that is now closer to the center pivot will experience an increase in input force equal to a decrease in the opposite master cylinder input force. This change in the ratio of input force will cause a change in the ratio of circuit pressures and therefore a change in the ratio of wheel end caliper output force.

The next step is to calculate the front and rear circuit master cylinder sizes:

22. Master cylinder size of the front circuit = two times the square root of the result of taking master cylinder input force and dividing it by the front circuit pressure and dividing also by π, or 3.142
23. Master cylinder size of the rear circuit = two times the square root of the result of taking master cylinder input force and dividing it by the rear circuit pressure and dividing also by π, or 3.142

From these calculations you can do some what-if scenarios. For example, it is possible to calculate what the maximum indicated gage pressure should be for either circuit. Of course, the answer will depend on your leg strength, the pedal ratio, and the master cylinder size:

Assuming that the pedal ratio and master cylinder size is as recommended (6.2:1 and 0.750 inch [19 mm]) and assuming the driver can leg bench press 600 lbs (300 on one leg), then 2100 psi would be the maximum gage pressure if no effort was lost due to any system compliance like the deflection of the pedal box mount or lack of caliper stiffness. In practice the maximum leg force possible is only around 120 lbs, which results in only 840 psi of circuit pressure. Even then, while most drivers are able to exert this much leg force without difficulty in the garage, it would be very hard to sustain this level for even a short race length.

Brake Pedal Setup and Dual Master Cylinder Installation

When the master cylinders are ready to be installed in the dual pedal arrangement, follow the manufacturer's directions exactly for the distance between the master cylinder pushrod clevises on the adjuster bar and master cylinder pushrod lengths. These are very serious setup steps that must be performed correctly.

As a general rule the distance between the master cylinder pushrod clevises on the adjuster bar must never be less than the distance between the master cylinder centerlines. In fact the distances should only be the same if the observed distance traveled by both of the master cylinder pushrods is the same. Otherwise, a slight increase in length between the clevises over the distance between the centerlines is recommended to make the pushrods parallel when the two circuits came to normal operating pressures. A difference between the distances of zero to +1/8 inch (0 to +3mm) is recommended. Any more will increase the side loading on the pistons and lead to premature piston to bore wear and seal failure.

In context with the pushrod lengths, care needs to be taken to adjust them so that under all circumstances both master cylinders come all the way back to their home positions when the brake pedal is released. It is often the case that one of the master cylinder pushrod is adjusted so that it prevents the piston from returning completely. This will result in the piston and piston lip seal being positioned in the bore so that the internal fluid porting does not refill the master cylinder properly when not in use.

This condition will be discovered in use when, after some pad wear occurs, the pedal begins to drop lower and lower. The problem can also be noticed as low flow or low pedal position when using gravity or pedal-pump and hold bleed methods respectively. Unfortunately vacuum and pressure bleeders will mask the problem until you are on the track and it is too late. In some cases the pedal mass alone will cause the partial displacement of one or both of the master cylinders off of the fully returned positions so a return spring needs to be added to compensate.

by Stephen Ruiz, General Manager of StopTech

STOPTECH

Stoptech is the performance engineering and manufacturing division of Centric Parts. It is the leader in Balanced Brake Upgrades for production cars and has three patents in basic brake technology and one other pending. With a worldwide network of resellers, StopTech's product line includes Balanced Brake Upgrades for approximately 450 applications featuring StopTech's own six-, four- and two-piston calipers, two-piece AeroRotor Direct Replacement Kits, braided stainless steel brake lines and slotted and drilled original-dimension rotors. StopTech also stocks a wide range of performance brake pads. The company's website, www.stoptech.com, is a clearinghouse of performance brake information, and provides details on StopTech products.

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