

TECHNICAL WHITEPAPER:

ABS and Big Brake Kits:

Fundamentals, Impacts and Real World Solutions

Anti-lock Brakes, Electronic Brakeforce Distribution, Vehicle Dynamics Control, Dynamic Rear Proportioning, Electronic Stability Program - the list goes on and on. With all of these integrated chassis control technologies now sprouting up on not-just-luxury-cars, maybe it's time we step back for a minute and have a look at what these systems consist of and what their sensitivities are...before we make changes to our cars which could potentially impact their performance. That being said, a little definition rollout is necessary so that we are all on the same page as we go forward with these discussions. This may be a little bit dry, but the good stuff is only a page or two away.

Definitions

ABS - Anti-lock Braking System

An electro-mechanical control system designed to monitor and influence wheel dynamics, and ultimately vehicle dynamics during braking maneuvers. In order of priority, these systems are intended to enhance vehicle 1) stability, or the prevention of oversteer 2) steerability, or the prevention of understeer and 3) stopping distance. Typical systems consist of 3-4 wheel speed sensors, an ECU containing the algorithm processing the wheel speed information, a series of solenoid-driven valves, and a pump-motor subsystem which can be actuated to interrupt and release brake fluid pressure from the wheel-end brake components (calipers and such).

TCS

Traction Control System - An electro-mechanical control system designed to monitor and influence wheel dynamics, and ultimately vehicle dynamics during acceleration maneuvers. In order of priority, these systems are intended to enhance vehicle 1) stability (RWD applications) 2) steerability (FWD applications) and 3) launch performance (all applications). Typical systems consist of 3-4 wheel speed sensors, an ECU containing the algorithm processing the wheel speed information, a series of solenoid-driven valves, and a pump-motor subsystem which can be actuated to build, hold, and release brake fluid pressure from the wheel-end brake components.

ESP

Electronic Stability Program (also referred to as VDC, IVD, TRAXXAR, and others not listed here) - An electro-mechanical control system designed to monitor and influence wheel dynamics, and ultimately vehicle dynamics during any vehicle state (braking, accelerating, or coasting). In addition to the sensors and hardware used during ABS and TCS, ESP typically utilizes the additional input from a steering angle sensor, a yaw rate sensor, and a lateral/longitudinal accelerometer when determining both 1) the driver's intended heading and 2) the vehicle's actual heading. Once the system has determined a significant difference (error) between (1) and (2) above, the solenoid-driven valves and pump-motor subsystem can be actuated to build, hold, and release brake fluid pressure at individual wheel-end brake components, creating asymmetric (cross-vehicle) brake forces in an attempt to create yaw moments, turning the vehicle toward the driver's intended path.

EBD

Electronic Brakeforce Distribution (also referred to as DRP, dynamic rear proportioning) - An electro-mechanical control system designed to monitor and influence rear wheel dynamics, and ultimately foundation brake (front-rear) balance. In so many words, the EBD utilizes the ABS hardware to function as an "intelligent brake proportioning valve." Unlike a traditional mechanical proportioning valve which is limited by design to one kneepoint and slope, the EBD algorithm relies on closed-loop feedback to continuously monitor rear wheel slip, adjusting brake line pressure to the rear wheels as appropriate.

Technology Dependency – ABS/TCS/ESP

The calibration of modern ABS/TCS/ESP is a complex and time consuming processes entailing the setting, or "tuning," of literally thousands of algorithm variables. These variables define the base vehicle characteristics (braking system included), control limits, and expected vehicle reaction to control activity. For this reason, one control algorithm may be utilized on several applications, but each vehicle requires its own unique variable set, or table.

Base vehicle dynamic response is of primary importance when tuning these variables, from a brake system, suspension system, and tire perspective. For example, the tuned and calibrated ABS expects certain vehicle reactions to its control signals. In simple terms, if the ABS control algorithm determines that a given wheel of the vehicle is in need of brake pressure reduction, it will calculate the amount of time required to actuate the pressure release solenoid based on the pressure-torque and/or pressure-volume characteristic of the wheel-end brake components. When calibrating the system, the Development Engineer essentially has to

"teach" these characteristics to the ABS, one tedious variable at a time. Press repeat for TCS and ESP.

Because the ABS/TCS/ESP implements "learning" logic to modify the next control cycle based on the activity in the current control cycle, any time spent "re-learning" these characteristics will ripple through the control cycles, with possible impacts to stability, steerability, and/or stopping distance. In short, changes in the base brake system characteristics (hardware) may impact ABS/TCS/ESP performance in any or all of these three areas.

Technology Dependency - EBD

Of the four technologies described herein, EBD may be the simplest to define, yet may carry the most wide-reaching impacts to base vehicle braking performance. While not nearly as variable-intensive as its ABS, TCS, or ESP counterparts, any time spent "re-learning" vehicle characteristics due to a change in the base brake hardware could possibly impact the vehicle brake system balance, or bias, during partial braking maneuvers.

Did I Just Read the Same Thing Twice?

Sounds like a lot of repetition, doesn't it? Truth of the matter is that these four control systems function in very much the same manner. Of course, there are numerous ways to implement each technology, and the technology suppliers have made it a point to do so, but when it all boils down we are dealing with chassis control systems which:

1. "evaluate" the driver's requests
2. "measure" what the vehicle is doing
3. "calculate" any difference, or error, between the two
4. "interact" in an attempt to make #2 equal #1

Now, instead of going through this next sequence for each technology on its own, let's look at the most common of the four - ABS - and see how changes to just our base braking system can wreak complete havoc on ABS performance. Once we understand just how sensitive the ABS control can be to the items listed above, the other three technologies fall into line. Here goes.

ABS Control in Super-Slow-Mo

In order to best explain how the ABS "depends" on the base braking system, let's have a look at a typical ABS event at the micro level - from the processing algorithm's perspective.

Say you are driving down the highway at 75 MPH (the posted speed limit, of course) when all of a sudden the truck in front of you spills its load of natural spring water across all three lanes of traffic. Now, this alone would not be so bad, except the water is still sealed in 55-gallon drums - one of which would certainly make a mess of your car's front fascia. Time to take evasive action.

Being the trained high-speed individual that you are, you immediately lift off the gas, push in the clutch (you are driving a manual transmission, right?), and simultaneously nail the brake pedal...but in the heat of the moment you hit it a little too hard.

Meanwhile, the ABS is hanging back watching the world go by, seeing a constant stream of 75 MPH signals from its four wheel speed sensors. Let's call this "observation mode." Upon your application of the brake, however, the ABS snaps to attention, its antenna up, ready for action. You have just hit the brake pedal after all, and who know what's coming next.

After 50 milliseconds (it's actually much faster than that - 7 to 10 milliseconds is typical - but it makes the math easier) the ABS takes another snapshot of the wheel speed information in an attempt to figure out what's going on. This time the wheel speed sensors are all reporting a speed of 74 MPH. Doing a quick calculation, the ABS determines that in order to have slowed 1 MPH in a 50ms period the wheels must be decelerating at a rate of 0.91g's. Because you are driving a sports car, the engineer who calibrated the system 'taught' the ABS that your car is capable of decelerating at this rate, so the ABS continues to hang back and watch the event from the spectator's booth. No problem so far.

The next 50ms, however, are a little more interesting. This time around, the wheels are reporting 72.5 MPH. Now, it may not seem like a big jump, but to slow 1.5 MPH in a 50ms window equates to a deceleration of 1.36g's. Not alarming, but the ABS 'knows' that based on this deceleration level, the wheels are probably beginning to slip a little more than they should - after all, your car is probably not decelerating at quite 1.36g's..and any error between the two indicates slip.

ABS is now in "ready mode." It's probably too soon to jump in, as the wheels might spin back up on their own in the next 50ms loop, but things are definitely looking bad!

As the first barrels of spring water bounce left and right, missing your car by inches, you stay on the brake pedal but push even harder. This time around, the left front wheel speed sensor is registering 68 MPH - a 4.5 MPH drop in the last 50ms, or a deceleration level of 4.1g's. Doing the math faster than you can (after all, you are busy dodging barrels of spring water), the ABS quickly comes to the conclusion that, unlike the left front wheel at this

moment, the car cannot possibly be decelerating at 4.1g's. Best case is that the car was decelerating at 1.0g (or thereabouts) over the last 50ms, so the 'real' vehicle speed is still somewhere around 71.5 MPH, even though the left front wheel speed is reading 68 MPH - a 3.5 MPH error.

So, based on a wheel deceleration of 4.1g's, a slip level of 5% (3.5 MPH 71.5 MPH), and a couple other factors not listed here, the ABS jumps in and enters "isolation mode." (Note that the wheels are nowhere even near "wheel lock" - the 100% slip point.) The first thing the ABS does is shut off the hydraulic line from the master cylinder to the left front caliper, isolating the driver from applying more pressure - after all, it was the driver that got us into this mess in the first place.

Next, the ABS starts work in "decrease mode," releasing the excess pressure from the left front caliper in order to allow the left front wheel to reaccelerate back up to the vehicle's actual speed - 71.5 MPH in this case. Since the ABS knows how quickly the wheel is decelerating (4.1g), how fast the car is actually going (71.5 MPH), and the pressure-torque characteristics of the left front caliper/pad/rotor assembly (we'll come back to this one in just a second), it can precisely calculate how long to open its release valve to vent that extra pressure, leaving just enough pressure in the caliper to maintain 1.0g of deceleration (or thereabouts).

Let's say that calculated time turned out to be 10 milliseconds (this again makes the math easier later on). Bang! Valve opens, pressure is released, and 10ms later it closes, leaving just the right amount of pressure in the caliper so that the wheel spins back up to exactly 71.5 MPH, but continues to decelerate at 1.0g. Everything is going as planned.

Time to close the loop and enter "increase mode." Once the ABS sees that the left front wheel has returned to near the 'real' vehicle speed, it slowly reapplies pressure from the master cylinder to make sure that maximum sustainable brake force is being utilized. To this end, the ABS calculates precisely how long to pulse open the isolation valve, slowly building pressure at the left front caliper until once again the left front wheel begins to slip. It performs this calculation based on - you guessed it - how quickly the wheel is re-accelerating, how fast the car is actually going, and the pressure-torque characteristics of the caliper/pad/rotor assembly. In our hypothetical little world, the ABS calculated that four pulses of 5ms each were necessary to build the wheel pressure back up to the point that the wheel began to slip again, returning to "isolation mode."

The cycle is repeated on all four wheels simultaneously until either the driver gets out of the brake pedal, or until the car has come to a stop. Hopefully, this did not include punting a spring water barrel or two along the way as the ABS kept all four wheels slips in the 5%-10% range, allowing you to turn and swerve to your heart's content as the drums bounced out of your path. Happy car, happy driver.

The Potential Impacts of “Big Brakes”

Let's now take the exact same scenario but add a twist: you are returning home from having that long-sought-after big brake kit installed. You know, the one that required new 18" wheels to clear the 8-piston calipers and 16" rotors. Driving around the parking lot you couldn't believe the improvement in pedal feel and initial bite they displayed. These things must really throw a boat anchor behind the car at high speeds, right?

Well, Let's See

Resisting the temptation to run in the fast lane at triple-digit speeds, you once again find yourself behind the spring water truck at 75 MPH. Barrels fly and you again lay on the brakes, but with the increased confidence of your new hardware to slow you down in time. Plus, you now know how the ABS works, so you lay into the pedal, confident that you will have both deceleration and steerability. It couldn't get any better.

Like scenario 1, after the initial 50, 100, and 150 milliseconds the ABS takes snapshots of the wheel speed information and registers 0.91g's, 1.36g's, and 4.1g's on the left front wheel. Again the ABS quickly comes to the conclusion that, unlike the left front wheel at this moment, the car cannot possibly be decelerating at 4.1g's. Best case is that the car was decelerating at 1.0g (or thereabouts) over the last 50ms, so the 'real' vehicle speed is still somewhere around 71.5 MPH, even though the left front wheel speed is reading 68 MPH - a 3.5 MPH error. So far, so good - just like last time.

Here's where things start to get interesting, though. ABS enters "isolation mode" and shuts off the hydraulic line from the master cylinder to the left front caliper, isolating the driver from applying more pressure. Next, the ABS starts work in "decrease mode," and once again calculates that 10ms are required to the excess pressure from the left front caliper in order to allow the left front wheel to reaccelerate back up to the vehicle's actual speed - 71.5 MPH in this case. Unfortunately, this calculation was based on the standard vehicle's pressure-torque characteristics of the left front caliper/pad/rotor assembly. Let's talk about this briefly while the barrels roll in closer.

Pressure-Torque and Pressure-Volume Relationships

When a braking system is designed and installed, the components are chosen to provide a certain deceleration level for a certain amount of force applied by the driver to the brake pedal.

While the overall relationship is critical, there are many ways to achieve the same end...but fundamentally the parts are chosen to work together as a system.

One of the most important relationships for the ABS engineer is the pressure-torque (P-T) relationship of the caliper/pad/rotor assembly. In so many words, for a given brake fluid pressure, X, the caliper/pad/rotor assembly will build up a certain amount of torque, Y. For the sake of argument, let's assume that adding 100 PSI of brake pressure to the stock caliper in our example vehicle generates 100 ft-lb. of torque.

Another important relationship is the pressure-volume (P-V) characteristic of the system. This relationship defines the swelling or expansion of the brake system for a given increase in pressure. Let's also say that our stock vehicle brake system 'swells' 1cc for every 100 PSI. Unfortunately, there are several big-brake systems available today which pay no regard to the original P-T or P-V relationships of the original vehicle...and in fact many make it a point to affect drastic changes in these relationships in order to give the consumer that feeling of 'increased bite.' While the upside is certainly a firmer pedal and higher partial-braking deceleration for the same pedal force, the trade-off can be ABS confusion.

Back to the Barrels

So, back to our example – the ABS has just calculated that a 10ms pressure reduction pulse was necessary to vent that extra pressure, leaving just enough pressure in the caliper to maintain 1.0g of deceleration (or thereabouts)...but the new system with its decreased P-V characteristics (increased stiffness!) releases twice as much pressure as the stock system in the same 10ms window (the equivalent of a 20ms pulse with the stock system)! Of course, the increased P-T characteristics (bigger rotor! bigger pistons!) don't help either, as now three to four times as much torque has been removed from the wheel as with the stock system, leaving only enough torque to decelerate the wheel at, say, 0.3g. In ABS land this is known as a 'decel hole' and feels just like you momentarily took your foot off the brake pedal.

Now, given that huge pressure decrease, the ABS quickly enters "increase mode," trying to correct and build the pressure back up near the vehicle's maximum sustainable brake force. This takes time and time equals lost stopping distance.

The ABS calculates precisely how long to pulse open the isolation valve and determines that four pulses of 5ms each are necessary, just like before. Because of the new P-T and P-V characteristics however, after only two pulses the wheel is again being forced into slip, leaving the ABS scratching its head and wondering what's going on. Not expecting wheel slip so soon, the ABS quickly releases pressure in an attempt to recover, but the damage has already been done.

The cycle is repeated on all four wheels simultaneously until either the driver gets out of the brake pedal, or until the car has come to a stop...but this time the ABS is always one step behind. In some cases the ABS is robust to modest changes in the base brake system, but in extreme cases there can be a significant negative impact to the vehicle's steerability (increased front wheel slip due to poor control) and a measurable increase in stopping distance (multiple 'make up' decrease pulses).

So, your chances of stopping in time or swerving to avoid one of the bouncing barrels have been decreased. In this game, inches count and you sure need every one.

TCS/ESP/EBD Impacts

The analogy above translates directly to the TCS/ESP/EBD subsystems without exception. Like the ABS, these three technologies rely heavily on the P-T and P-V characteristics of the OEM system, and any changes can manifest themselves under braking, accelerating, or dynamic maneuvers.

Are You Telling Me That Big Brakes Are a Bad Idea?

So, will all big brake upgrades wreak havoc on the chassis control systems found on your favorite ride? Not necessarily. In fact, if designed and chosen properly, these upgrades can make the most of these control technologies while providing all of the cooling and thermal robustness advantages these kits have to offer.

The "secret" to brake system compatibility is that there is no secret - it just requires fundamental engineering expertise and design know-how.

As mentioned earlier, far too many of the big brake upgrade kits on the market today pay no attention to the P-T or P-V characteristics that the car originally possessed. In fact, there are kits available today which have P-T characteristics which more than double the output ($P \Rightarrow 2T$) of the stock systems they replace - "200% More Stopping Power" must be better than stock, right? In most cases, these vendors procure large quantities of big rotors and red calipers, fabricate an adapter bracket to mount them to a variety of different suspensions, and market the kit as a 'one-size-fits-all' without first determining if the system will be compatible with the remaining foundation braking system, let alone the electronic chassis controls. Sure, it's quick, cost-effective, and looks like a million bucks through your 18" wheels, but what about ultimate performance?

The Solution

Unlike the "if it works on brand P, it must work on your car" approach, at StopTech all brake upgrade kits are designed with the characteristics of the original braking system taken into account to minimize these differences. This is the reason that when you order a StopTech big rotor upgrade kit the new caliper bores may actually be smaller than the units you are replacing to "balance the equation." This is just one way in which our engineers attempt to retain the original system's P-T and P-V integrity. Sure, it's not one-size-fits-all, but neither is your car...or your driving style. Why should you expect any less from your brake upgrade?

In closing, next time you think about bolting on those 16" rotors and 8-piston calipers remember that there are a number of chassis control systems out there just waiting to be confused. Select wisely and reap the benefits.

by James Walker, Jr. of scR motorsports, exclusively for StopTech

James Walker, Jr. is currently the supervisor of vehicle performance development for brake control systems at Delphi Energy & Chassis. His prior professional experience includes brake control system development, design, release, and application engineering at Kelsey-Hayes, Saturn Corporation, General Motors, Bosch, and the Ford Motor Company. Mr. Walker created scR motorsports consulting in 1997, and subsequently competed in seven years of SCCA Club Racing in the Showroom Stock and Improved Touring categories.

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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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