Brakes
ARG19 Fall Technical Report
December 15, 2018
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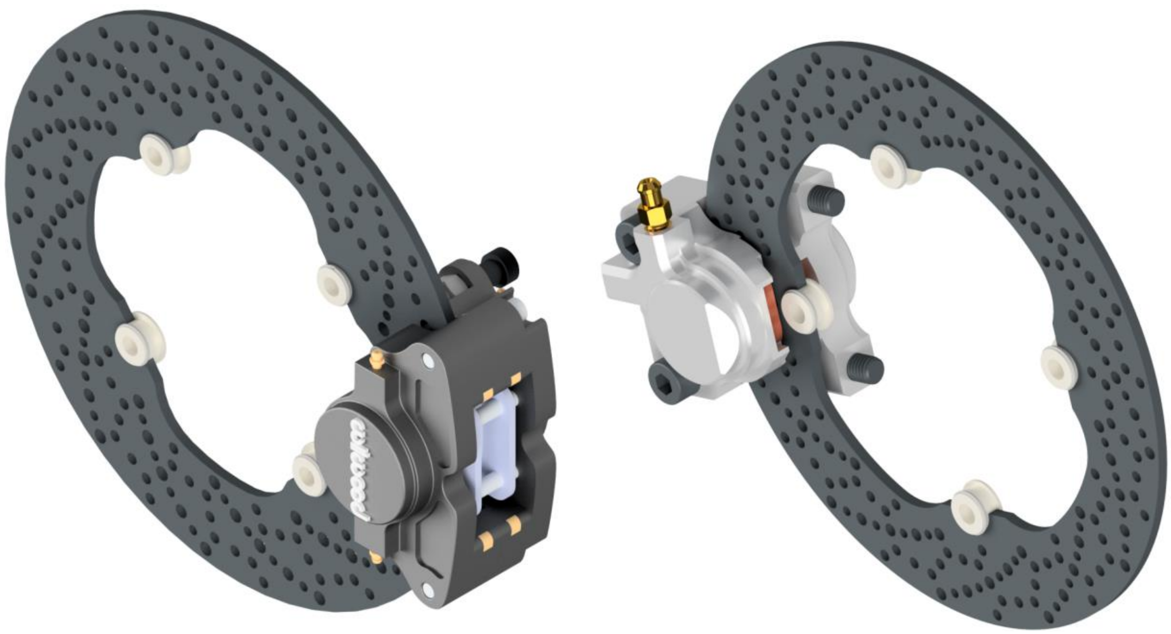

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0. Introduction

Brakes have a simple function – stopping the vehicle. The typical avenue for accomplishing this is conversion of the vehicle's kinetic energy into heat energy through friction. There are a few reasons why this method is so popular, but the main reason is that slowing a vehicle via frictional force allows for gradual deceleration - the magnitude of which depends on the input (normal) force from the operator. A simply binary brake proves insufficient for passenger vehicle applications as such a system is unpleasant for passengers, and certainly the same is true for racecar applications, however a more present concern is the need for varying deceleration magnitude in transient scenarios or even varying track conditions.

From a driver's standpoint, braking is the most difficult concept to master in car racing. I remember around a decade ago during a Formula 1 race broadcast Martin Brundle said 'Racing is 90% braking and 10% knowing when to press the throttle.' The logic follows that the precision of the braking system needs to be considerable. Having a reliable and consistent braking system is of the utmost concern for designers who care about drivability.

For a reliable brake system, each design component or selected part must be chosen with reliability in mind. As such, it helps to have a more holistic understanding of what comprises a general braking system. The most obvious assembly is the arresting mechanism. This includes the caliper, friction material, disc/drum, and the mounting associated with either a disc or drum. Drum brakes have been relegated to irrelevancy in professional racing applications by the popularity of the disc brake, and the same is true for Formula SAE. Drum brakes are too heavy and relatively complex compared to disc brake setups, and are also considerably more prone to fade because the friction/drum contact path is largely unexposed to cooling air – completely unacceptable in high-performance applications. [1]

The friction material for disc brakes usually arrives as a pad on either side of the disc that clamps with driver input, creating a frictional force to arrest the wheel's motion. The friction material mounts inside a caliper that is either fixed or floating. A fixed caliper features hydraulic pistons on each side of the rotor, both connected to a high-pressure hydraulic system and capable of producing a variable force. A floating caliper only has hydraulic connections on one side (typically the side closer inboard), while the non-hydraulic side has a second pad securely mounted without hydraulic connection. The whole caliper mounts on pins, leaving it some translational freedom in the y-axis. When the connected piston actuates, the floating portion of the caliper translates on the pins and moves closer to the disc, thus clamping onto the rotor.

FSAE 18-19 rules require that the braking system not be brake-by-wire and have two separate hydraulic circuits (exclusive front/rear wheel circuits are the assumption). This hydraulic system is assumed unpressurized and free of air (incompressible) without driver input. Only when the driver begins to press the pedal should the pistons output a force, clamping the rotor in between the two pads. The driver input force is converted into pressure via a master cylinder, which has a piston within a known bore size pressing against the hydraulic fluid.

The brakes system rules for the FSAE 18-19 competition season are relatively unchanged with respect to those from the 17-18 season:

T.5 BRAKE SYSTEM

T.5.1 General

T.5.1.1 The vehicle must be equipped with a braking system that:

a. Acts on all four wheels

b. Is operated by a single control

c. Must be capable of locking all four wheels

T.5.1.2 The braking system must have two independent hydraulic circuits such that in the case of a leak or failure at any point in the system, effective braking power is maintained on at least two wheels.

T.5.1.3 Each hydraulic circuit must have its own fluid reserve, either by the use of separate reservoirs or by the use of an OEM style reservoir.

T.5.1.4 A single brake acting on a limited slip differential may be used.

T.5.1.5 "Brake by Wire" systems are prohibited.

T.5.1.6 Unarmored plastic brake lines are prohibited.

T.5.1.7 The braking systems must be protected with scatter shields from failure of the drive train (see **T.7.2**) or from minor collisions.

T.5.1.8 In side view any portion of the brake system that is mounted on the sprung part of the vehicle must not project below the lower surface of the chassis

T.5.1.9 Fasteners in the Brake system are **Critical Fasteners**, see **T.10.2** and **T.10.3**

T.5.1.10 The brake pedal must be:

a. Fabricated from steel or aluminum OR machined from steel, aluminum or titanium.

b. Designed to withstand a force of 2000 N without any failure of the brake system or pedal box.

This may be tested by pressing the pedal with the maximum force that can be exerted by any official when seated normally.

T.5.1.11 (EV only) Additional requirements for Electric Vehicles:

a. The first 90% of the brake pedal travel may be used to regenerate brake energy without actuating the hydraulic brake system.

b. The remaining brake pedal travel must directly actuate the hydraulic brake system. Brake energy regeneration may remain active.

c. Any strategy to regenerate energy while coasting or braking must be covered by the FMEA

T.5.2 Brake Over Travel Switch - BOTS

T.5.2.1 A Brake Over Travel Switch (BOTS) must be installed such that brake pedal travel exceeding the normal range will actuate the switch

T.5.2.2 The BOTS must be a mechanical single pole, single throw (commonly known as a two position) switch (push-pull or flip type).

T.5.2.3 Actuation of the BOTS to the OFF position must:

a. (IC) Shutdown the engine(s) and fuel pump(s) **IC.8**

b. (EV) Shutdown the Tractive System **EV.7.2**

T.5.2.4 Repeated actuation of the switch must not reset or restore power

T.5.2.5 The BOTS must be designed so that the driver cannot reset it.

T.5.2.6 The switch must be implemented with analog components, and not using programmable logic controllers, engine control units, or similar functioning digital controllers.

1. Technical Overview

Much of what I learned concerning designing the brakes system came from a selection of handy texts from the online SAE Library. I compiled all of these into one folder which is included in the folder where this report is located on the S: Drive (Reports > ARG19 > Unsprung >Brakes).

Assuming that the current ruleset is used and a set of disc brakes is desired, the essential flow for the design process of the brakes system begins with some basic vehicle dynamics. Depending on how accurate of measurements (or projections) of the car exist, a very good mathematical model can be made to aid design of the system. This mathematical model should model the car in different braking scenarios and back-calculate the balance of the input force on the master cylinders. This portion of the process requires the following vehicle parameters:

- CG Height
- Wheelbase
- Weight Distribution
- Aerodynamic efficacy at each axle (optional)
- Tire/road interface coefficient of friction
- Tire dynamic radius
- Vehicle mass

This mathematical model may also help guide the selection of the following parameters:

- Brake rotor diameters
- Master cylinder bore diameters
- Brake caliper bore diameters
- Brake pedal mechanical advantage

Once this preliminary analysis is completed, components may be selected to fit the parameters set. This method of analysis is common, and has been around for many years. [1]

Moving on, the bulk of the component selection should be complete. After this point, most of the effort in designing the brakes system should be put into designing a successful rotor, analyzing fasteners, and working with the hub and upright designers to make sure that small interferences are avoided. The first step for designing the rotor is choosing a mounting system. Floating rotors, radially mounted free rotors, and mounting to a hat are all common methods for fixing the rotor in place.[1] Next, geometry should be considered – something which involves a large amount of static structural analysis in ANSYS. Once all of these are complete, the thermal compatibility of the rotor must be analyzed. Many models have been developed for this – none are perfect, but some get closer than others, and the selection of a thermal model depends greatly on the information available to the designer. To predict the overall heat input to the brake rotor, a very common method is to use a lumped parameter model, however it requires testing in order to fully describe the system. Reasonable attempts at estimating the necessary values may be used as substitutes, but exercise caution. [2] Designing the brake rotor then becomes a balancing act of reducing mass and increasing reliability, which can be iteratively acted on until the design is satisfactory. The final step of the design is mounting the entire system. Hopefully this will have been thought about along the way, in which case it becomes easy to design.

2. *History of Past Designs*

For the entirety of the ARG16 chassis cycle (including 17 and 18), the team used the same basic system components (Wilwood PS-1, APRacing 4226, and APRacing CP7855). Dating even further back, the team has been using the same ideology for as far as I cared to go back in the reports – fixed calipers with two separate hydraulic circuits and either a floating or bolted connection between the hub and the rotor. I have nothing against that, as the system itself was well-thought out and fairly well implemented. Fortunately, this year the Unsprung team became a well-staffed subteam, and we were able to devote more time to this system which is good because the car is changing massively compared to last year. The largest change is the vehicle's mass – up around 50 lbs from last year – as well as fairly different hub geometry allowing for some changes to the rotors' geometry. In terms of changes that were made this year, the system's basic ideology is the same, but components have changed completely. This is not due to performance issues on ARG18, but due to the drastic changes to ARG19 requiring a redesign, and a large majority of these changes were made with a mathematical model similar to the one outlined in the Technical Overview section.

3. *Data*

The need for data in the design of the Brakes stems from a need to demonstrate the degree of correlation between simulation and real-world in design. As such, the data needed becomes simple:

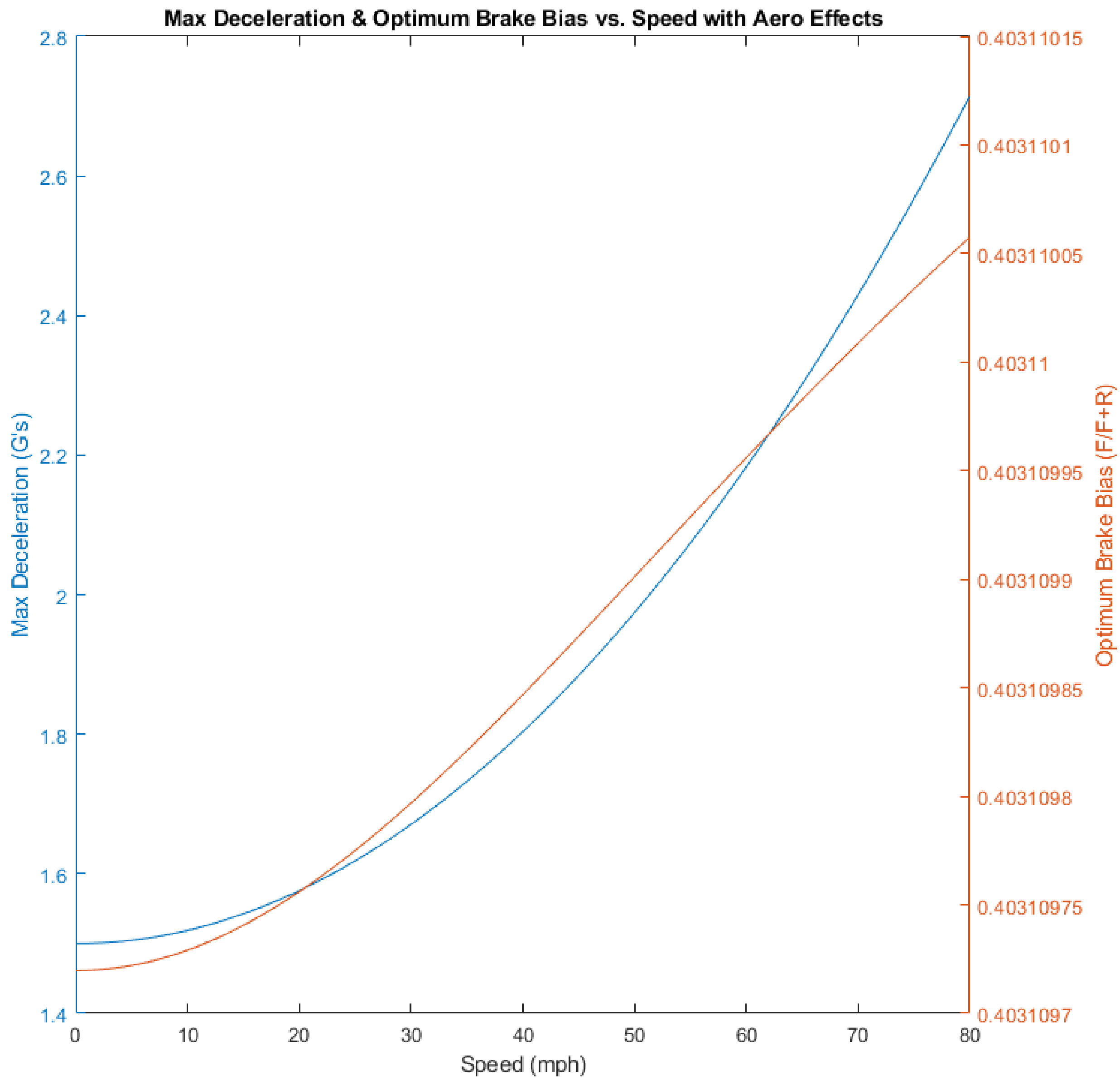
- Pad Mu vs. Rotor Temp vs. Pad Temp
  - We care about this because it demonstrates that your car will remain drivable throughout the temperature cycles that it sees. Pairing this surface with a "worst mu scenario" analysis is wise. This is something that Kern recommended in 17, and really something that I should focus on next semester.
  - Testing for this involves a simple pad dyno – no inertial loading necessary, just a motor, disc, pad, and some thermocouples.
- Rotor Temp vs. Time during driving
  - This data constitutes the ability to show correlation between your design and the real world – being able to show that the conversion of kinetic energy into heat energy is occurring as expected. This testing comes from a driving day, where the rotor temperature is logged and a model is formed to mirror the heating and cooling cycles seen during that drive. Comparing the two should yield correlation if the model is generated correctly, and it should lead to changes in the model if correlation is not met.

4. *ARG19 Design*

The design I have chosen for ARG19 is not too far from that of ARG18, mostly with updated component selection/sizing. After a failed attempt to attain a new sponsor for a material known as SSAB Domex 550MC – a Trip Steel – the material for the brake rotors will be staying the same as ARG18, however this year I have been able to acquire a sponsorship from Incodema to waterjet-cut the rotors for us using a Bevel-Capable machine. This will hopefully allow us to alleviate the issues from past years where the edge of the rotors ended up non-square. In terms of the actual design process, the most significant portion of the component selection was done using a MATLAB script I made (comparable to those made in years past, but far more organized and infinitely more commented) that chose basic parameters as I outlined in the technical overview section. I have plans to continue fleshing out this MATLAB script during the spring semester so that I can continue to develops plots that will be beneficial to us during Design at competition.

Below is a plot generated by the script as well as the input parameters used. The plot shows the bias, from the bias bar, necessary to achieve simultaneous lockup at both axles and maximum deceleration vs. speed. The goal of the system was to have 50% F/R be the default to achieve simultaneous lockup, and 40% is not quite good enough. This happened because my initial component selection used an "effective" tire mu of 2.0 based on the Parameters & Analysis set out by Sebastian Bauco. For such a tire, the resultant bias was 50% F/R. However, when the actual tire mu is used in conjunction with a coefficient for aerodynamic downforce at each axle, the default bias shifts massively because the forces at each axle are now drastically different (even at the same 2.0G deceleration). We may have to change the size of the rear circuit's master cylinder to account for this, but technically the range of the bias bar will allow us to achieve the necessary bias.

Parameter	*Value*
CG Height	.279m
Wheelbase	1.65m
Weight Distribution	.55 (Rear)
Tire/Road Mu	1.5
Tire dynamic radius	.229m
Vehicle Mass	273.9kg
Front Aero "Coefficient"	.034 lbs/mph^2
Rear Aero "Coefficient"	.042 lbs/mph^2
Front Rotor Diameter	.176m
Rear Rotor Diameter	.165m
Front Master Cylinder Bore	.0178m
Rear Master Cylinder Bore	.0254m
Front Caliper Bore	.000793m^2
Rear Caliper Bore	.000491m^2



If I had more time to work on this design I would have done more to generate a thermal model. Specifically, nailing down a Pad mu vs. Pad Temp vs. Rotor Temp plot would be amazing. That as well as actually having something to show in the way of a thermal model would make this a design I am confident in taking to have judged at competition. My focus for the next semester should be those two things – one can be done off car but the other will rely on being able to run the car reliably for the duration of a test. At the very least I can perform the test with 18, achieve correlation, then apply the same analysis to 19 with some degree of confidence.

5. Components Overview

Part	Material	Vendor	Machining
Front/Rear Rotors	Nodular Iron 80-55-06	Siemens	Incodema
Brake Keys	Titanium 6Al-4V	OnlineMetals	In-House

Part	Selected Component	Part No.
Front Caliper	Wilwood GP200	120-12178
Rear Caliper	ISR 22-049	22-049
Front Master Cylinder	Tilton 76 Series .7”	76-700
Rear Master Cylinder	Tilton 76 Series 1”	76-1000
Brake Key Retention	Smalley Spirolox Rings	ES-12

22-049 2-piston caliper

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The 22-049 caliper was originally designed to be used for Motocross bikes but the caliper is also suitable for all kinds of lighter bikes and cars . It can be used in a one or two caliper brake system.

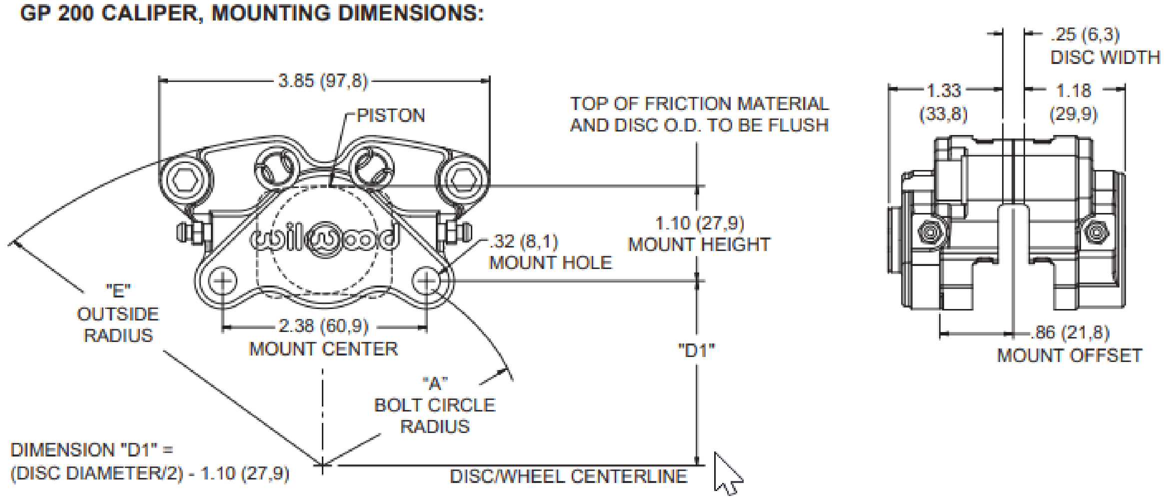
This caliper has only got a 27 mm height of the swept disc area. This means the disc can be made light. It also means that the brake disc gets a clean "low profile" design.

Technical data

Part number (Click on Part# to view image)	22-049-OA (RH) 22-049-OB (LH) 22-049-OC (RH car) 22-049-OD (LH car)
Piston diameter	25 mm (x2)
Piston material	Tufram coated aluminium alloy
Pad type	ISR 29-002 (x2)
Pad area	7 cm2
Swept height of disc	27 mm
Disc size	150 - 250 mm
Disc thickness	4.6 - 5.0 mm
Hydrualic threads	M10 x 1.25
Weight incl. pads	0.29kg
Surface finish	Clear anodised

ISR 22-049 Datasheet

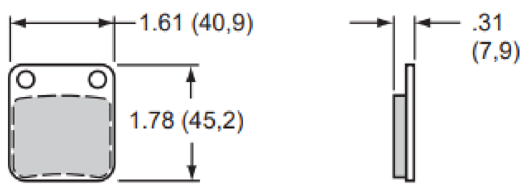
GP 200 CALIPER, MOUNTING DIMENSIONS:



INLET FITTING: 1/8-27 NPT

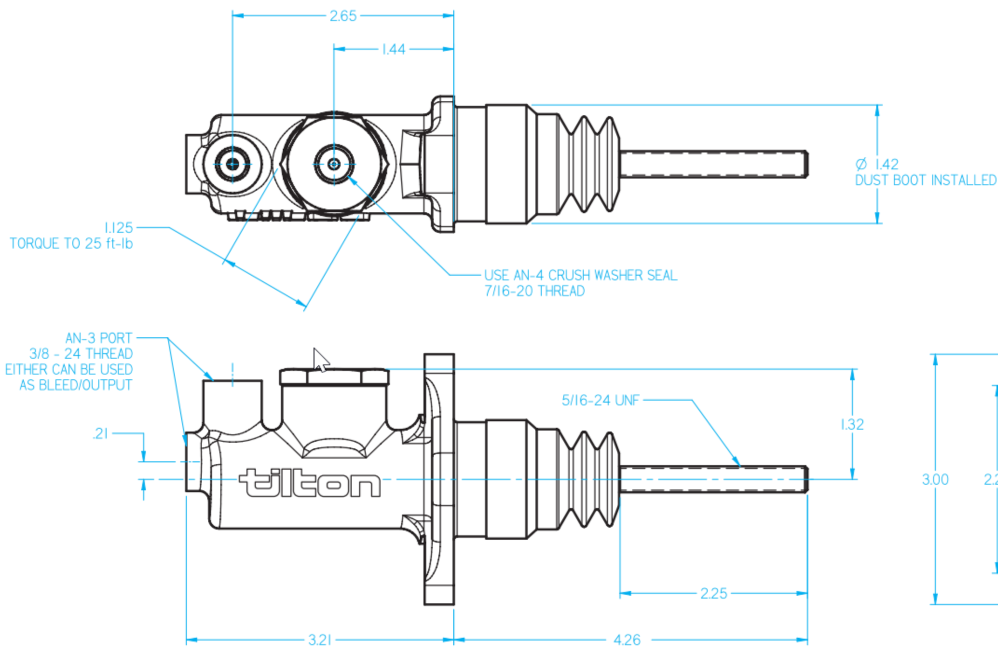
DISC DIAMETER	"E" OUTSIDE RADIUS	"D1" HEIGHT	"A" BOLT CIRCLE RADIUS
8.00 (203,2)	4.68 (118,9)	2.90 (73,7)	3.13 (79,5)
8.75 (222,2)	5.03 (127,8)	3.28 (83,2)	3.48 (88,4)
10.00 (254,0)	5.62 (142,8)	3.90 (99,1)	4.07 (103,4)
10.50 (266,7)	5.86 (148,9)	4.15 (105,4)	4.31 (109,6)
10.75 (273,0)	5.90 (149,9)	4.28 (108,6)	4.43 (112,6)
11.00 (278,4)	6.10 (155,0)	4.40 (111,8)	4.57 (115,0)

GP 200 CALIPER, TYPE 4908 PAD DIMENSIONS AND ORDERING INFORMATION:



AXLE SET PART NO.	PAD TYPE / COMPOUND
150 - 12270K	4908 Purple Pad for Aluminum Rotor
150 - 12128K	4908 CM Composite Metallic

Wilwood GP200 Datasheet



Tilton 76 Series Datasheet

6. References

[1] F. Puhn, *Brake Handbook*. Los Angeles, CA: HP Books, 1985.
[2] D. Sheridan, J. Kutchey, F. Samie, *Approaches to the Thermal Modeling of Disc Brakes*. Warren, MI: SAE Global, 1988.