Design and Fabrication of Hydraulic Braking System for Formula Student Vehicle

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Abstract: Present paper encompasses design of a hydraulic braking system with a pedal box. The system is designed for a single person formula student vehicle weighing 250kg. The objective of the system is to convert the kinetic energy into thermal energy allowing the vehicle to decelerate safely. The paper is divided into various categories namely; calculation and evaluation of the hydraulic system in order to select calipers and master cylinders, the design of the pedal box, the design of the rotors and manufacturing the components.

After the calculation it was found that the braking torque required for the vehicle to stop after considering load transfer is 150 Nm and 130Nm for front and rear tires respectively. Willwood master cylinder was selected which provided hydraulic pressure of 4.89Mpa to the front brake lines and 4.17Mpa to the rear brake lines. Vespa calipers were selected with two pistons which provided braking force of 8022.32 N at the front calipers and 6559.332 N at the rear calipers. Pedal box was designed consisting a brake pedal and two master cylinder mountings. It is designed for minimum mass and maximum strength.

1. Introduction

Braking systems are designed to one specific task that is they need to bring to a halt the moving vehicle.In theory the principle is very easy. Brakes convert the kinetic Energy of the moving body into heat energy that then gets transported into the sorroundings.Since the advent of wheels the mechanisams to stop it has existed and is yet to be changed even today.Early brakes were derived from the designs used in the horse-drawn carriages but as the cars became more powerful and faster theses designs were no longer viable.Early desiigners only equipped rear wheels with brakes because of the difficulty in designing the braking system on a wheel having a steering mechanism in place already.These design were largely inefficient because at the instant of braking the front tyres are the one which require larger braking force because of the weight transfer that occurs during braking.Hence braking systems,equppied only on the rear tyres,took much larger distances to bring the vehicle to a halt.The early braking systems also used mechanical actuators but after the advent of hydraulic actuating systems around 1920 these mechanical actuating systems were replaced.Though mechanical systems remained in the racing applications because of their simple design,greater reliability and ease of maintainence.

In road racing particularly braking systems are of immense important to the safety and performence of the driver. Consequently braking systems litrelly determines the outcome of the races.When it comes to drag and the oval races the braking systems will have their additional challenges and would needed to be designed accordingly. Here in this paper we intend to demonstrate our paradigm for design and fabrication of the braking system for Formula Student Racing car.Since this is a student competition the cars competing have significanntly lower power and and top speed owing to budget constraints.Hence fabrication of these brakes is to be done within the constraints.

2. Braking system

The specific function of the braking system is to convert the Kinetic Energy of the moving vehicle into the Heat Energy.

2.1 Kinetic Energy of Rotation

Strictly speaking, an object with kinetic energy can be either moving in a straight line or be rotating about its center Center of Gravity (CG). In a speeding car Kinetic Energy is mostly in

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the moving car.(CG).Unless the car is spinning down the road, less than 10% of the total kinetic energy is stored in rotating parts of the car. Rotating parts include tires, wheels, brakes, engine and drive line. Additional kinetic energy stored in these rotating parts must be absorbed in the brakes. However, to make calculations simpler, we ignore the small amount of the kinetic energy stored in the moving parts.

Type of Energy	Example
Heat	Energy stored in a hot brake rotor.
Sound	Noise from exhaust.
Light	Light from headlights.
Stored Mechanical	Energy stored in a compressed coil spring.
Chemical	Energy in a gallon of gasoline.
Electrical	Current from a battery turning a starter.
Radiation	Microwave energy in a microwave oven.
Kinetic	Energy stored in a speeding bullet.

Fig. 1: Source of Energy

Although the mechanisam of braking remains the same and unchanged.But the braking systems do differ in mechanisms they use to apply friction and get rid of the resulting heat that has been generated due to the friction. These are either the drum brakes or the dic brakes or the combination of both that are used on the vehicles.
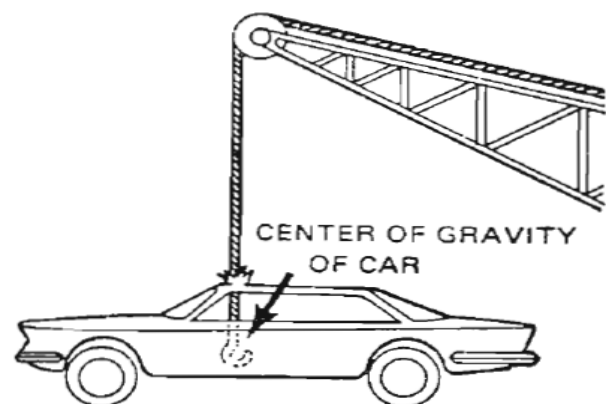
Fig 2: Center of Gravity of car

Brake pedal controls the master cylinder which pressurizes the fluid in each of the slave cylinder.Slave cylinder then push the calliper to grab the rotor for the braking action to happen.A

hydraulic system has two functions:move brake linings into postions against drum and rotor and apply force to brake linings to create friction force.

External drums were used before but due to their difficult maintainence internal drum brakes evolved where the brake shoe is present inside the drum. When the driver applies force on the brake pedal,friction is generated between the shoe and the drum. Disc brakes are different than the drum brakes in many ways. Disc brakes have a rotating disc that is attached onto the wheel hub and when the driver pushes the brake pedal the attached calliper grabs the disc with some force. The fricition thus generated helps in halting the vehicle. Apart from these their are brake actuating systems that must be discussed before desigining the brakes.These systems come into picture between the short instant when the driver applies force onto the pedal and there is friction generated. These systems could be mechanical, hydraulic, pneumatic or a combination of these. But all of these systems start at the brake pedal linkage. This is where the driver applies force. Brake pedal could long that decreases the amount of force required to apply the brake but they have long travel which could lead to sponginess in the braking. Trade offs must be made to have the perfect brake pedal as per the application. Mechanical actuating systems are one the simplest braking acctuating systems. Brake pedal operates the cables or rods which apply the brakes when the pedal is pushed.These kinds of brakes are still used in parking brakes of the pasenger vehicles. Modern cars use the hydraulic actuating system where the cables and rods are replaced by the fluid-filled lines and hoses.
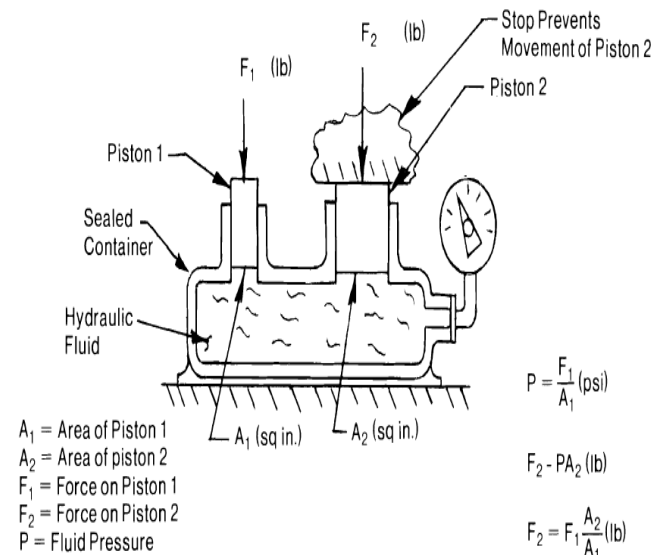
Fig 3: Basic of Hydraulic

2.2 Literature Review

Barakat [1] conclude that maintaining the brake slip friction parameter before attaining the wheel to lock up similar to ABS performance curve; to minimize the stopping distance by adjusting the whole vehicle parameters, needs to be calibrated on a real time event during the brake test during the formula student UK by using Matlab image recognition to measure the change of the wheel angular velocity during braking.

Belhocine and Bouchetara [2], analyse the thermo mechanical behaviour of the dry contact between the brake disc and pads during the braking phase. The simulation strategy is based on computer code ANSYS11. The modelling of transient temperature in the disc is actually used to identify the factor of geometric design of the disc to install the ventilation system in vehicles. The thermo-structural analysis is then used with coupling to determine the deformation established and the Von Mises stresses in the disc, the contact pressure distribution in pads. The results are satisfactory when compared to those found in previous studies.

Sowjanya and Suresh [3] considered disc brake is made of Cast iron, so it is being selected for investigating the effect of strength variations on the predicted stress distributions. Aluminium Metal Matrix Composite materials are selected and analysed. The results are compared with existing disc rotor. The model of Disc brake is developed by using Solid modelling software Pro/E (Creo-Parametric 1.0). Further Static Analysis is done by using ANSYS Workbench. Structural Analysis is done to determine the Deflection, Normal Stress, Vonmises stress.

Parab et al [4], Disc (Rotor) brakes are exposed to large thermal stresses during routine braking and extraordinary thermal stresses during hard braking. The aim of the project is to design, model a disc. Modelling is done using catia. Structural and Thermal analysis is to be done on the disc brakes using three materials Stainless Steel and Cast iron & carbon carbon composite. Structural analysis is done on the disc brake to validate the strength of the disc brake and thermal analysis is done to analyze the thermal properties.

Patel et al [5] analysed the thermo-mechanical behaviour of the brake disc during the braking phase and used coupled thermal-structural analysis to determine the deformation and the Von Mises stress established in the disc to enhance performance of the rotor disc.

Bill [6] optimized the brake pad friction material, it show experimental verification of the realized brake system for the racing car BRC08, particularly in the design of the brake discs and their thermal load.

Pritam et al [7] considered functions properties of brake disc or rotors for the initial screening of the candidate materials using Ashby's materials selection chart and showed the highest performance index for AMC 2 material using digital logic method.

Swapnil R. Abhang, D.P.Bhaskar [8] ,carbon ceramic matrix disc brake material use for calculating normal force, shear force and piston force and calculating the brake distance of disc brake. The standard disc brake two wheelers model using in Ansys and done the Thermal analysis and Modal analysis also calculate the deflection and Heat flux, Temperature of disc brake model.

Venkatramanan et al [9] work deals with the thermal analysis of disc brake of a vehicle. Heat generation and dissipation of disc brake are analysed. They investigated and analyze the temperature distribution of rotor disc during operation using Ansys.

3. Design Requirement

The design requirements [10] as per the rules of formula student are as:

- The brake pedal must be fabricated from steel or aluminium or machined from steel, aluminium or titanium.
- It 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.
- Each hydraulic circuit must have its own fluid reserve, either by the use of separate reservoirs or by the use of a dammed, OEM-style reservoir.
- Single brake acting on a limited-slip differential is acceptable.
- The brake system must be capable of locking all four wheels during the test.
- The brake pedal shall be 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.
- Calculating maximum braking capacity of vehicle means maximum possible deceleration of vehicle based on tyre model.
- Calculate desired braking ratio between front and rear wheels for locking of all the four wheels at the same time.
- Selection of material and dimensions for brake disc considering structural and thermal stresses.

3.1 Design Process

Under the braking condition the vehicle is moving in the direction of its front tires, the greatest deceleration rate will translate as a weight transfer from the rear tires to the front tires. Therefore, it is

necessary to calculate this weight transfer based on the average coefficient of friction between the tires and the road, the weight of the vehicle, the height of the center of mass above the road, and the wheelbase. This weight transfer will be denoted as Ft and calculated.

Table 1: Vehicle Suspension Data

Wheelbase(l) = 1.575m	Tire radius (Rt) = 0.2286m
CG height (h) = 0.305m	Horizontal CG = 1.796
Front Track (Tf) = 1.35m	Coeff. of Friction = 0.4
Rear Track (Tr) = 1.335m	Static Weight (Front) = 981 N
Weight (w)=250kg =2452.5 N	StaticWeight(Rear)= 1471.5 N
C.o.f(road-tire) (u)= 0.7	% Distribution at front and rear SW(f) = 0.40 ; SW(r) = 0.60

Dynamic Load Transfer (1g Braking) =Ft= $\dfrac{uMgh}{L}$

Dynamic Load Transfer= $\dfrac{(0.7*250*9.81*0.3048)}{1.575}$ = 331.22 N

With the help of DLT, we can calculate dynamic weight trader to front and back.

Dynamic weight transfer front = static weight front + Ft

DWF=981+331.22=1312.22 N

Dynamic weight transfer rear = static weight front - Ft

DWR= 1471.5-331.22=1140.3 N

Percentage biases on front and rear wheel

Kb (f) = 0.54

Kb (r) = 0.46

Now, braking torque from the front and rear wheels can be calculated as

$TF = (\dfrac{DWF}{2})*Rwheel =150$ Nm

$TR = (\dfrac{DWR}{2})*Rwheel=130.3$ Nm

3.2 Master Cylinder Selection

Pressure exerted by the master cylinder is equal to the product of the pedal force to the bore diameter of the master cylinder. While selecting the master cylinder the bore diameter was taken to be a free variable. At first, the bajaj master cylinder was used but the bore size of the master cylinder was less and they were less reliable in a race like situation. Therefore, The Wilwood master cylinder was selected because of its easy availability and was tested worldwide. The bore diameter of the master cylinder is 15.9 mm. Considering the driver applied the force of 300N and pedal having leverage of 6 then,

force at the master cylinder = 300*6 = 1800 N

Pressure in the master cylinder is equal to the ratio force on master cylinder to the bore area

$= \dfrac{1800}{198.45}$ = 9.07 MPa

Pr. in the front brake lines = biasing * total pressure

= 0 .54 * 9.07 = 4.89 Mpa

Pr. in the rear brake lines = biasing * total pressure

= 0.46 * 9.07 = 4.17 Mpa

3.3 Caliper Selection

The number of pistons in the caliper and the coefficient of friction of the brake pads were the free variables for these selections. After considering various factors such as weight, number of pistons, cost and size, Vespa calipers were selected.

Number of pistons on caliper = 2

Diameter of piston of caliper = 32 mm

Area of piston = 803.84 mm^2

Force at Front caliper = Pr. in master cylinder * Area of piston Caliper * No. of pistons

= 4.99* 803.84 * 2 = 8022.32 N

Force at Rear caliper = Pr. in master cylinder * Area of piston Caliper *No. of pistons

= 4.08* 803.84 * 2 = 6559.332 N
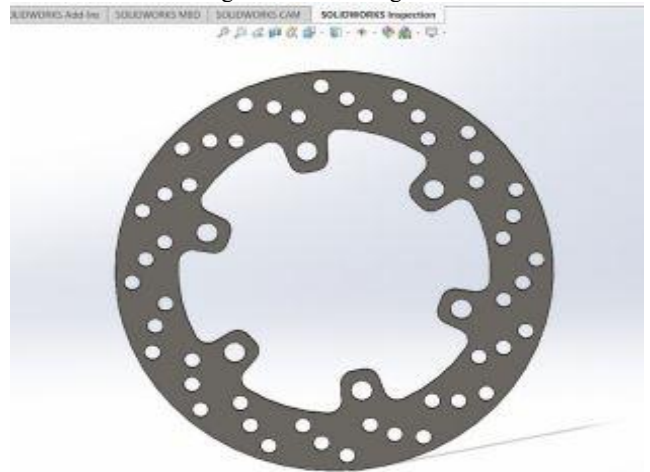
3.4 Rotor Design

The radius of the rotor is decided by taking into account the size of the caliper and the constraints provided by the suspension department for the hub used.

Braking Torque Received (Front) = Force at Front Caliper*Effective Rotor Radius= 166.05 Nm > Required torque

Braking Torque Received (Rear) = Force at Rear Caliper*Effective Rotor Radius = 135.77 Nm > Required torque

There were two concepts that were taken into account for selecting the rotor geometry:

i. The cut pattern needed to wear the brake pad relatively uniformly, as a deformed pad would cause the contact surface between the pad and the rotor to decrease, thus inhibiting the effectiveness of the braking system.

ii. Decreasing the mass of the rotor needed to be optimal; that is, there is a certain amount of material that can be removed where the rotor has enough mass to endure the heat transfer and there are enough cuts for venting.
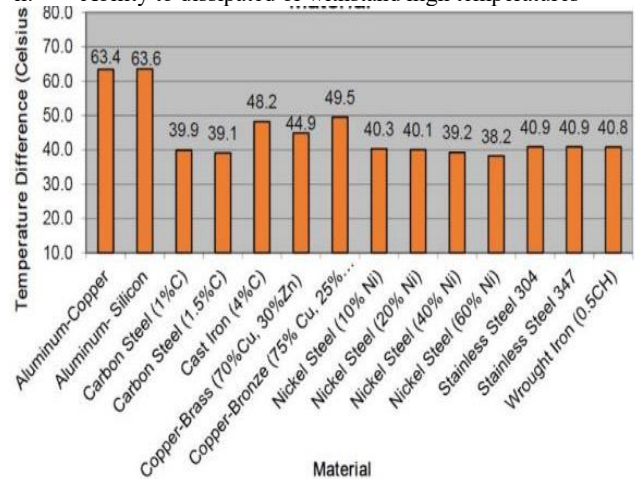

Fig 4: Selected Rotor Design

3.5 Material Selection

Basic criteria for material selection of rotor are:

i. Mechanical endurance at high temperatures

ii. Ability to dissipated or withstand high temperatures

Fig 5: Temperature change in rotor v/s rotor material

Based on the application, a metal, ceramic or composite material was assumed to be optimal, however based on the team's budget a metal was the only realistic choice. In order to make a selection, the conservation of energy was employed only for the linear motion of the vehicle at its maximum velocity to compare the temperature

change of the rotors between materials. In this calculation it was assumed that each rotor would share evenly in the overall heat transfer. This is not the actual case; however for the purpose of comparison this method was utilized.

Kinetic energy=Thermal energy

$$\frac{1}{2} M_1 V^2 = \text{(no. of rotors)} * M_2 * Cp * \Delta T$$

Putting, M_1 = 250kg

V = 16.6 m/s

Number of rotors = 4

$$\Delta T = \frac{17222.5}{M_2 * C_p}$$

To calculate temperature change, variables which are strictly dependent upon the material of the rotor.

4. Results and Discussions
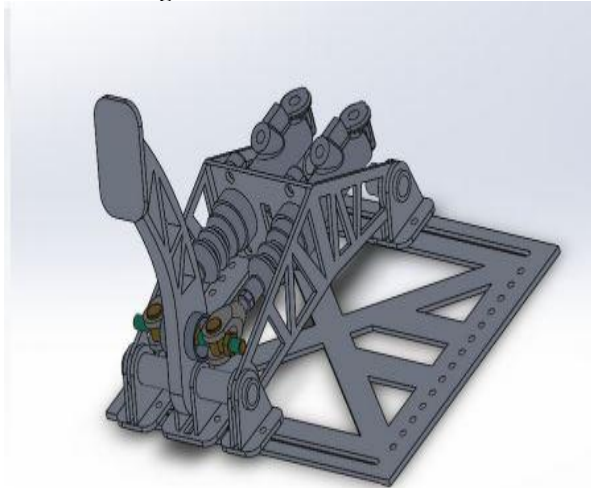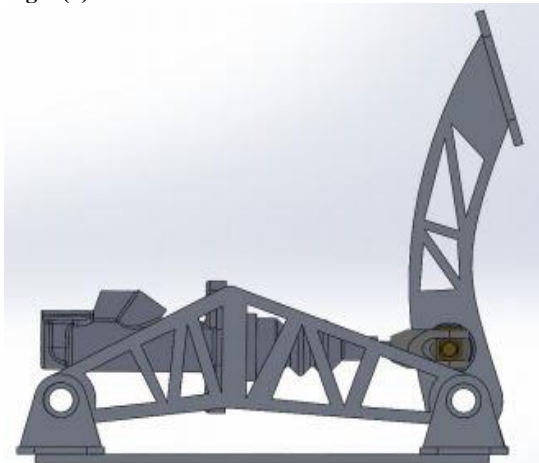### 4.1 Final Design

Fig 6 (a): Standard View

Fig 6 (b): Side View

4.2 Simulation
The following figures show the FEA stress on rotor, pedal, base plate and master cylinder mounting:

▪ Rotor

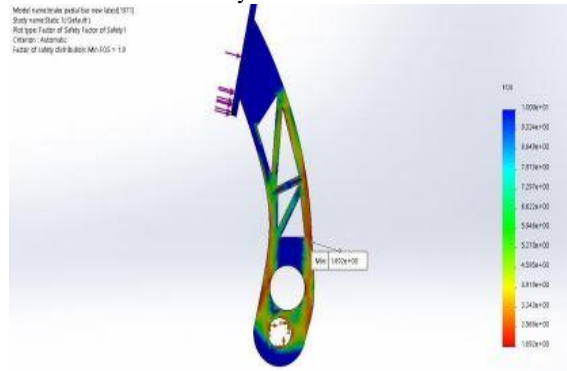

Fig 7: Rotor Analysis

▪ Pedal
Factor of Safety : 1.9

Fig 8: Pedal Analysis
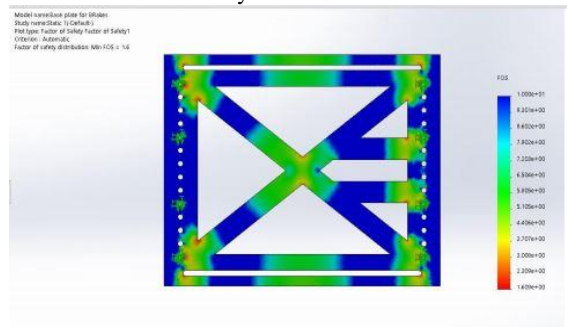
▪ Base Plate
Factor of Safety: 1.6

Fig 9: Base Plate Analysis

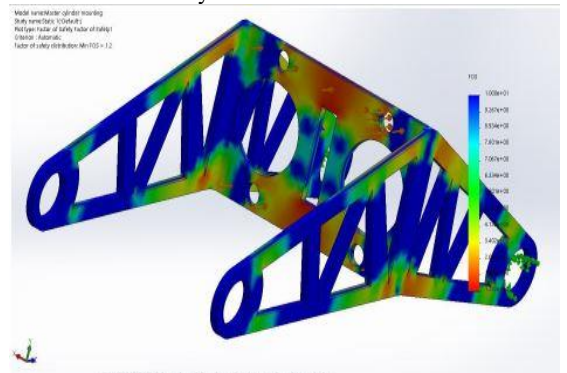▪ Master cylinder mounting
Factor of Safety: 1. 2

Fig 10: Master Cylinder Mounting Analysis

4.3 Fabrication
The parts manufactured have different dimensions and applications and hence some of them have been made with different procedures than others.

4.3.1 Rotor
The plates of rotors have been made by the process of laser cutting.It is a column of very high-intensity light typically of a single wavelength.The diameter of the beam is also small,about three fourth of an inch.Focusing the laser beam is done by a special lens, or by a curved mirror, and this takes place in the laser cutting head. The beam has to be precisely focused so that the shape of the focus spot and the density of the energy in that spot are perfectly round and consistent, and cantered in the nozzle. By focusing the large beam down to a single pinpoint, the heat density at that spot is extreme. The high power density results in rapid heating, melting and partial or complete vaporizing of the material. When cutting stainless steel or aluminium, the laser beam simply melts the material, and high pressure nitrogen is used to blow the molten metal out of the kerf. Cut quality can be affected by raising or lowering the focal point from just

above the surface of the plate, at the surface, or just below the surface.

Fig 11(a): Manufactured Rotor Plate

Fig 11 (b): Manufactured Rotor Plate

4.3.2 Pedal

The pedal for brakes has been manufactures using the 6-axis milling.This operation is slightly different from the more common 3-axis and 5-axis milling process.In the 3-axis milling process the cutting tool moves in the 3-perpendicular axis and in the 5-axis milling the tool,in addition to the 3-axis rotates around the x and y axis as well.And in the 6-axis milling it rotates around the z-axis also making the process much faster and efficient.

Fig 12: Manufactured Pedal

5. Conclusions

In conclusion the hydraulc braking system according to the design parameters of the formula student competion was designed and fabricated.The braking systems for the front and the rear wheel are symmetrical.The parts chosen were well under financial constraints.Designs were simulated in Dassault Systems SolidWorks and further static analysis for the required strength of

the material was obtained from the same.The resulting braking system was fabricated as shown in figure with thw following parts.

- Wilwood master cylinder was chosen for the hydraulic actuating system
- Vespa calipers(Floating calipers single piston) were finalized which provide the required force for grasping the rotor for braking action.
- Rotor material chosen is A36 carbon steel which provide the sufficient strength and enough weight so not to fail at event of braking.

Factor of safety so obtained from the Simulation
Base plate for pedal box:1.6, Plate for master cylinder mounting:1.2, Brake pedal:1.9.

Abbreviations

DLT	=	dynamic load transfer
DWF	=	dynamic weight transfer front
DWR	=	dynamic weight transfer rear
TF	=	torque front
TR	=	torque rear
Pr.	=	pressure
U	=	coefficient of friction
M	=	mass of vehicle
G	=	centre of gravity height
L	=	wheel base
M_1	=	mass o the vehicle
V	=	speed of the vehicle
M_2	=	mass of rotor
Cp	=	heat capacity
ΔT	=	temperature change

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