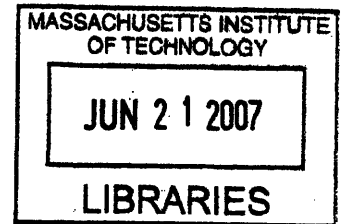# 2007 Formula SAE Pedal Box

By

Brad W. Schiller

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN
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BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
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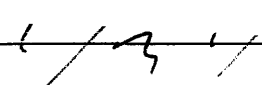MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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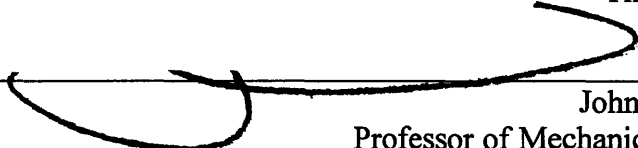
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ABSTRACT

The purpose of this thesis is the design and implementation of the pedal box for the 2007
MIT Formula SAE car. Formula SAE is a collegiate competition in which groups of
degree seeking students design and manufacture small formula style race cars to compete
on design, cost, marketing, and performance. The pedal box is an integral part of the
vehicle as the driver directly interacts with it making ergonomic considerations integral to
the success of the design.

The 2007 pedal box design emphasizes design for manufacture, adjustability, ergonomics
and weight savings. An innovative design decreases the amount of space needed for the
pedal box through the use of vertically mounted master cylinders while allowing for the
driver to adjust front to rear brake bias, brake pedal ratio, and location in the car. The
design also causes a significant reduction in complexity and weight through a decrease in
the number of components needed for manufacture.

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1.0 The Formula SAE Competition

Formula SAE is a collegiate design competition that encompasses more than 300 teams from around the world that compete in 8 different competitions located across the globe. The purpose of the competition is to design and manufacture a small, formula style race car. Every year each team must build a new vehicle in order to compete. The purpose of this is to ensure that teams reengineer their vehicles each year to guarantee learning. The Society of Automotive Engineers (SAE) that puts on the event every year outlines rules for the competition to ensure that teams compete on an equal playing field. While the rules ensure the safety of the participants, the rules are still left open enough to encourage innovation and a great amount of design diversity throughout all of the different vehicles.

The competition consists of both static and dynamic events. The static events consist of cost, design, and marketing. The dynamic events consist of acceleration, skid pad (lateral acceleration), autocross (1 km), and endurance (22 km). In addition to these events, the vehicle must pass a technical inspection, noise test, brake test, and lilt table test in order to compete.

Of particular importance to the design of the pedal box are the cost, design and dynamic events. There is a total of 1000 points in the competition of which 30 points are related to the cost, 150 points to the design, and 675 points are directly related to the performance of the vehicle in the dynamic events. Due to the tremendous point differentials, the focus of the design of the pedal box relies heavily on performance, then design, with cost being a minor consideration.

2.0 Design Philosophy and Methodology

The constraints of the need to design and manufacture an entire racecar on a limited budget with a small team over the course of only a year places a large burden among those individuals participating in the process. In order to continue to improve from year to year in the final standings, designs must become more innovative, possibly more complex, and must be designed and manufactured in a timely manner every year since much of the competitions final score can be impacted by good driving. In order to achieve these results, it is imperative to transfer knowledge from year to year due to the short duration each individual has to impact the team before graduation.

The goal of this thesis is to develop a pedal box that future generations of vehicles can use with very minimal design changes. The thesis will outline reasons for design decisions, part selection, material selection, as well as provide the all of the analysis to back up the decisions. It is important that the design contains several innovations as it is important to stay ahead of the curve in the competition and if the design will be used as a building block for future year's designs, it must contain new concepts that will take a while for other teams to catch up with. This thesis will provide a solid foundation for pedal box design for year's to come.

The calculations for the pedal ratios are done with Matlab since it is necessary to go through complex geometric analysis. Once all of the geometry is set, the design of the actual part is done using Solidworks with the FEA on certain key components being done in Cosmosworks. The FEA is done using an iterative process in order to optimize the design. Once the design is complete, the team manufactures the components and assembles the pedal box for testing to verify the design.

2.1 Functional Requirements

The pedal box must provide the driver with a means of braking and accelerating. It may also contain the clutch. If the pedal box does not contain the clutch, then the clutch must be placed on the shifter. To accommodate drivers of all sizes, the pedal box must be adjustable. The pedal box needs to house the master cylinders and reservoirs for the brake fluid. The structure that master cylinders attach to must be able to take enough force through the master cylinders that can lock up all four wheels. Driver feel must be considered in the design meaning there is a need to minimize hysteresis in the system and consult with the drivers to see what they like best.

2.2 Design Parameters

The pedal box system has many constraints put on it by both other components in the car, Formula SAE competition rules, and score considerations. The competition rules that affect the pedal box are:

3.2.5 Brake Systems

The car must be equipped with a braking system that acts on all four wheels and is operated by a single control. 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. "Brake-by-wire" systems are prohibited. A single brake acting on a limited-slip differential is acceptable. The braking system must be protected with scatter shields from failure of the drive train or from minor collisions. Unarmored plastic brake lines are prohibited.

3.2.5.1 Brake over Travel Switch

A brake pedal over-travel switch must be installed on the car. This switch must be installed so that in the event of brake system failure such that the brake pedal over travels, the switch will be activated and will stop the engine from running. This switch must kill the ignition and cut the power to any electrical fuel pumps. Repeated actuation of the switch must not restore power to these components, and it must be designed so that the driver cannot reset it. The switch must be implemented with analog components, and not through recourse to programmable logic controllers, engine control units, or similar functioning digital controllers.

By the rules, the brake system must contain two independent hydraulic circuits. This means that there must be two master cylinders housed in the pedal box, one for the front brake system and one for the rear brake system. The pedal box also needs to contain an over travel switch for the brake system. When the brake pedal travels to far, the switch triggers and kills the power to the car.

Two major constraints are imposed by the mass and cost budgets of the entire car. Before the design begins on every component, the team management assigns a weight and cost goal to each component. The overall weight of the vehicle gives benefit in the design judging and performance. The first impression the design judges get when they first the car besides its aesthetic is the sticker on the front that tells the car's weight. In general, vehicles must weight under 500 lbs in order to be considered remotely competitive in the design competition. Due to the increasing level of competition every year, it is anticipated that in order to make it to design semi-finals, the car must weigh less than 450 lbs. For perspective, the 2005 MIT Formula SAE car weighed 449 lbs. The car that won the design part of the competition was Penn State University whose car weighted 376 lbs with the same engine that the MIT team uses. The lighter the car is, the more impressed the design judges are and the higher the design score will be. For performance, a lighter car means faster acceleration and better handling around turns. The power to weight ratio is the key to the competition so every lb saved in the design of a

component gains more points to the overall score than about $500 less on the overall cost report.

The mass budget for the 2007 MIT Formula SAE car is 430 lbs. According to the mass budget, the pedal box, shifter, seat, body, and dash must weigh a combined 25 lbs. Given the probable weights of the other ergonomic components, the pedal box may weigh a maximum of 5 lbs.

The cost budget is the final cost of the pedal box that appears on the cost report of the car. The cost of the pedal box should not exceed $600 out of a total car cost of $17,000. This constraint can only be broken if there is a significant advantage that can be gained do to increased cost. According to the equation used to determine the score given to a car based on the cost reported, $500 in costs is worth about one total point in the final score.

The frame and human body are the major constraints that determine the size and location of the pedal box. The pedal box may not extend beyond the bulkhead plane of the car. It must fit between the lower frame rails that extend from the lower suspension point to the bulkhead. It must move along these rails as to accommodate different drivers.
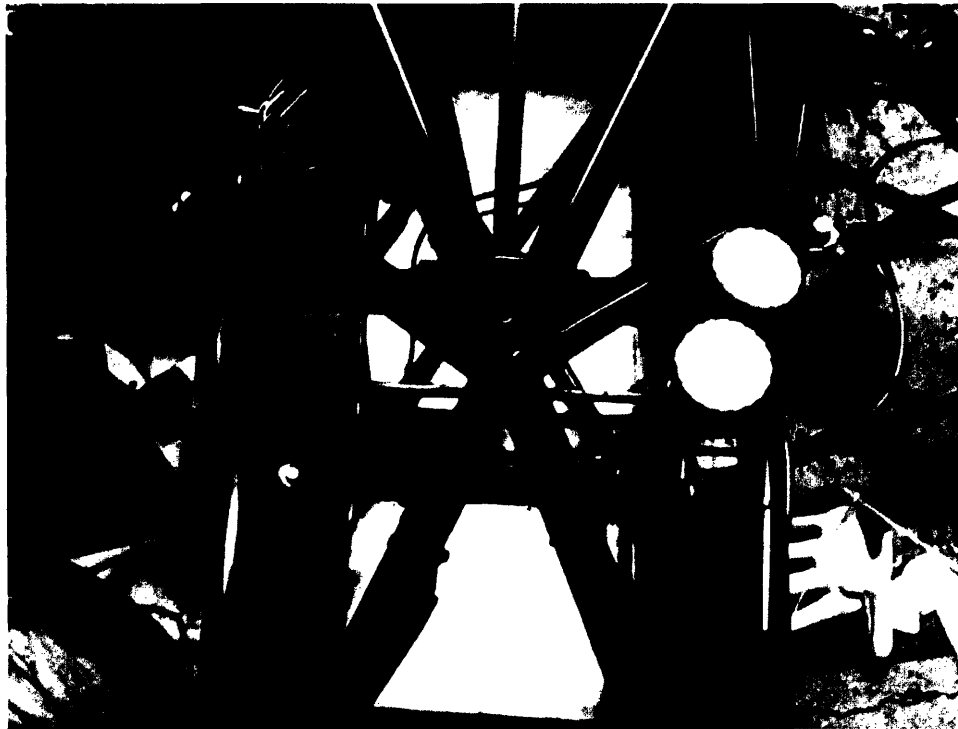
Figure 1: Frame Location where Pedal Box Attaches

The size and position of the driver's feet determines the height and angle of the pedals. The average length of a human foot from the heel to the ball is 7.5 in. The pedal pad must be located at the ball of the foot. The pedals need to travel about 2.5 inches in order to accommodate foot movement while maximizing the pedal feel.

The brake pedal places the largest forces on the pedal box frame. The master cylinders feed brake fluid to the brake calipers. The pressure in the system needs to reach 815 psi for the front and 496 psi for the rear in order to lock all four wheels. The forces created by displacing the fluid in the master cylinder go into the pedal box frame. The pedal box frame is designed around the brake pedal because of the large force. The force applied by the human to lock the wheels should be about 100 lbs from driver experience.

2.3 Interdependencies with other Systems

When designing the pedal box, it is imperative to take serious consideration of the interdependencies with other systems in the vehicle. The pedal box contains a large number of interdependencies and its design could add more weight to another component of the car than the savings gained in the pedal box. The design must take the interdependencies into consideration and look at any weight savings or performance gains in the context of the whole vehicle rather than just the pedal box. The following subsections cover all of the systems that interact with the pedal box.

2.3.1 Frame

The pedal box must fit between the two lower frame rails the run from the lower front suspension to the bulkhead. The frame needs to accommodate the full length of the pedal box plus room for adjustability. The pedal box moves along the frame rails and needs to attach into these frame rails at different locations. The frame has square rails for this purpose that may be drilled to serve as attachment points for the pedal box. Since these rails must be have a wall thickness of at least .049" and a diameter of at least 1 inch, a safety equivalency form must be filled out with the calculations to prove that E.I. of the square tube with the holes drilled in it is at least that of the tube required by the rules. A copy of the filled out safety equivalency form is located in Appendix A. The pedal box must position the driver's feet so that the feet fit within the top frame rails and between the lower frame rails. This makes a protection envelope for the driver's feet.

2.3.2 Crash Structure

Per the rules, the master cylinders may not be located beyond that bulkhead (the front most plane of the frame) of the car. The pedals initial position cannot be beyond the bulkhead as well. This means that when the pedals are pressed down at full travel, they can be beyond the bulkhead if this is desired. The rules also state that a crash structure to absorb any impact must be in front of the bulkhead. If the pedals are to extend beyond the bulkhead when in full travel, then the crash structure must be made to accommodate a pedal traveling in the middle of it.

2.3.3 Ergonomics

The positioning of the driver in the seat drives the positioning of the pedal box. If the driver has their knees bent, their feet will be able to produce different angles than if the legs were straight. The driver knee positioning determines the initial pedal angle as there exists a foot angle that gives the maximum amount of force transfer from the driver. The position of the break pedal in full travel should be located at this foot angle. The distance from the seat to the pedal box depends on the positioning of the driver. If the driver's knees are bent, the pedal box should be located closer to the seat.

2.3.4 Brakes

The brake system has the most interdependencies with the pedal box. The pedal box must house two master cylinders that determine the pressure in the brake lines. The pressures needed in the brake lines in order to lock up all four wheels during the brake test are 815 psi for the front and 496 psi for the rear. The balance bar that connects to the master cylinders needs to be housed within the pedal box. The pedal box may contain the reservoirs for the brake fluid. The reservoirs feed additional fluid to the master cylinders. If not located within the pedal box, the reservoirs should be mounted above the master cylinders and out of the way of the driver's feet and legs. The master cylinders should be in a position that does not make bleeding the brakes difficult. The brake pedal and frame must take a force large enough to lock up all four wheels.

2.3.5 Intake

The accelerator interacts with the throttle body on the intake system. The throttle cable which is a basic pull cable attaches the throttle body to the accelerator. The pedal box must have a mount for the cable casing. The accelerator must connect to the cable,

without the cable interfering with the driver's foot. The pedal must return to its original position when a force is not applied. The cable must go back to its initial position as well. The cable should be located where the driver cannot cause it to bind.

2.3.6 Engine

If the clutch is part of the pedal box, then there is an interaction with the clutch on the engine's transmission. The interaction acts in much the same way that the intake works. The sheath of the pull cable is mounted to the fame of the pedal box. The cable inside the sheath attaches to the clutch pedal. The clutch pedal must return to its original position once the driver takes his foot off the pedal.

2.3.7 Electronics

The pedal box is integrated into the electronics system because of the rules that requires the brake pedal to have an over travel switch that kills all power and the engine and the requirement of a brake light. The brake over travel switch is connected to the pedal box frame and the wiring must be integrated into the electronics diagram. There must be a pressure sensor located along the hydraulics system that connects into the wiring harness and causes the brake light to light up when the brakes pedal is pressed.

3.0 Initial Concepts

The pedal box design should be based around the master cylinders and brake pedal. The largest forces are taken into the pedal box frame from the master cylinders and brake pedal. The force on the pedal box from the accelerator and clutch is negligible. There are basically three different positions that the master cylinders can take. These consist of mounting the master cylinders forward of the pedals, rearward of the pedals, or at an angle (commonly referred to as vertically mounted cylinders even through the cylinders are not mounted perfectly vertically) Outlines of the three different design concepts follow in this section along with a discussion of the location of the clutch as the clutch can be added to any of these designs.

3.1 Master Cylinders Forward

Placing the master cylinders forwards (away from the driver) of the brake pedal is the most conventional location. An overwhelming majority of the teams competing in the Formula SAE competition use this master cylinder positioning. A sketch is in Figure 2.

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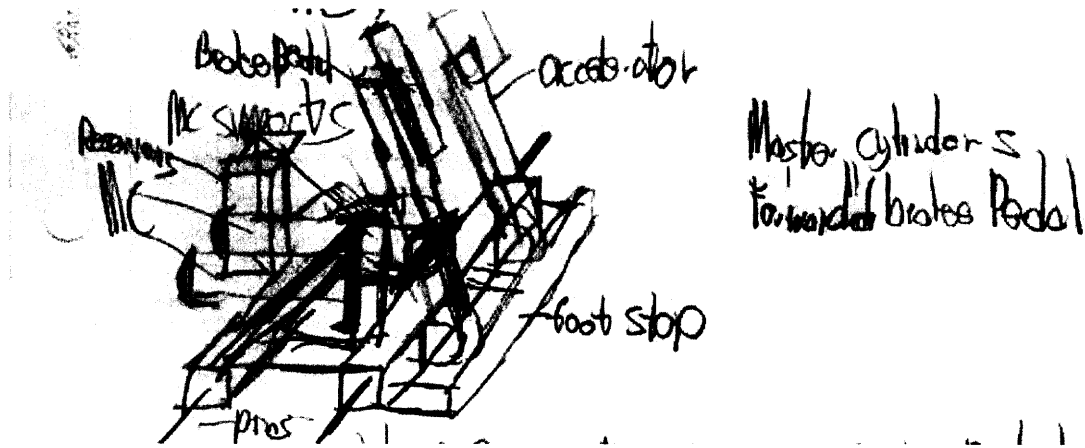
Figure 2: Forward Mounted Master Cylinders

The benefits of the design are that it is a very inexpensive way of doing the design. The master cylinders can be push type meaning that pushing the rod into the master cylinder will increase pressure in the system. The reservoirs can mount directly on top leading to less plumbing required. AP Racing CP2623 master cylinders run about $140 each. The master cylinders also bleed easily from this position. The overall design is very simple and easy to manufacture. The forces are easy to understand and the pedal ratio can be calculated by just taking the length of the pedal over the distance from the pedal pivot to the attachment point of the master cylinders. The design is very simple and the only really good way to reduce the weight is to just optimize the frame and pedal design.

The design does leave a lot to me desired. The master cylinders are quite long leaving the distance from pedal pivot to the end of the pedal box to be around 7 inches. To accommodate for the length, the frame of the car must be longer and therefore extra weight is added to the frame through this design. There is extra weight in the design since the master cylinders are flange mounted leading to increased complexity in the pedal box frame design. The foot stop is not integrated into the frame itself leading to extra weight and manufacturing time. The design requires four pins to hold it in the car's frame and the force acts towards the front or back of the car indicating that the pins take the entirety of the load. The use of four pins means the design is over-constrained and therefore it may be difficult to drill all the frame holes correctly. Since the design is very simple and not noteworthy, the pedal box will not earn extra points in the design presentation part of the competition. The weight of the entire system can probably be just around 5 lbs.

3.2 Master Cylinders Rearward

Placing the master cylinders rearward of the brake pedal (towards the driver) can be done in two different ways. Either, the foot can be placed between two push type master cylinders if the brake pedal pivot is located above the master cylinders. Another solution is to use pull type master cylinders located below the foot. Pull type master cylinders would have to have remote reservoirs and are a lot more expensive than push type master cylinders. A sketch is shown in Figure 3.
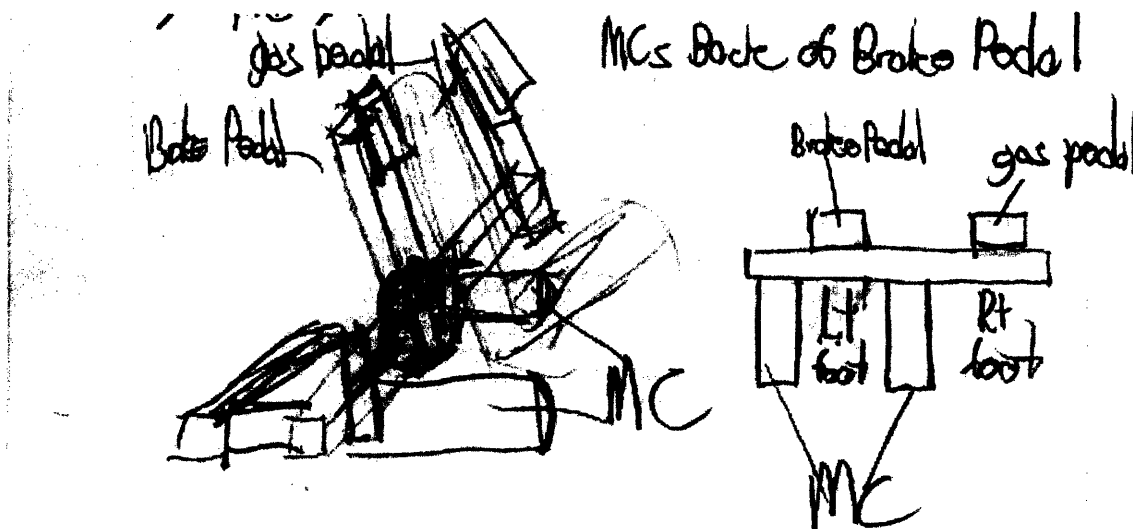

Figure 3: Rearward Mounted Master Cylinders

The primary benefit of mounting the master cylinders rearward of the brake pedal is the reduced length from the break pedal pivot to the front of the box. This allows the frame to be shortened by about 7 inches decreasing the overall frame weight by about 3 lbs. If done right, this is a fairly novel design since it isn't done by many teams and could increase the number of design points the team gets.

There are many difficulties with the design. If push rod master cylinders are used (AP Racing CP2623 as described above), the pedal pivot needs to be placed relatively high, making the pedal ratio a maximum around 3:1. Also, the master cylinders need to be placed far enough apart for the driver's foot to fit between them. This creates a large moment on the balance bar meaning that the balance bar will need to be strengthened. Also, there isn't much room between the driver's feet in general and the frame may have to be wider in order to accommodate the changes. The driver's feet could be placed above the master cylinders as well, but then the frame will have to be made a couple inches taller. Push rod master cylinders would lead to easy bleeding in the case of the foot

between the master cylinders but difficult bleeding if the feet are above the master cylinders. The cylinders would have to be modified to have remote reservoirs increasing the amount of plumbing needed

Using pull rod master cylinders would be around $300 per cylinder but would not need remote reservoirs. The pull type master cylinders solve the problem of the low pedal ratio that the push types have when the frame isn't raised. Another issue is that the diver's left foot must be located between the master cylinders causing numerous problems with the frame width and feet hitting the master cylinders and plumbing.

3.3 Master Cylinders Angled

Placing the master cylinders at an angle with the brake pedal is an unconventional design that only a couple teams use. The design is made possible through the relatively recent advent of spherical bearing mounted cylinders. These master cylinders have a spherical bearing in the rear enabling the master cylinder to rotate. The spherical bearing mounted master cylinders are very expensive and run from $290-$675. The sketch is shown in Figure 4.
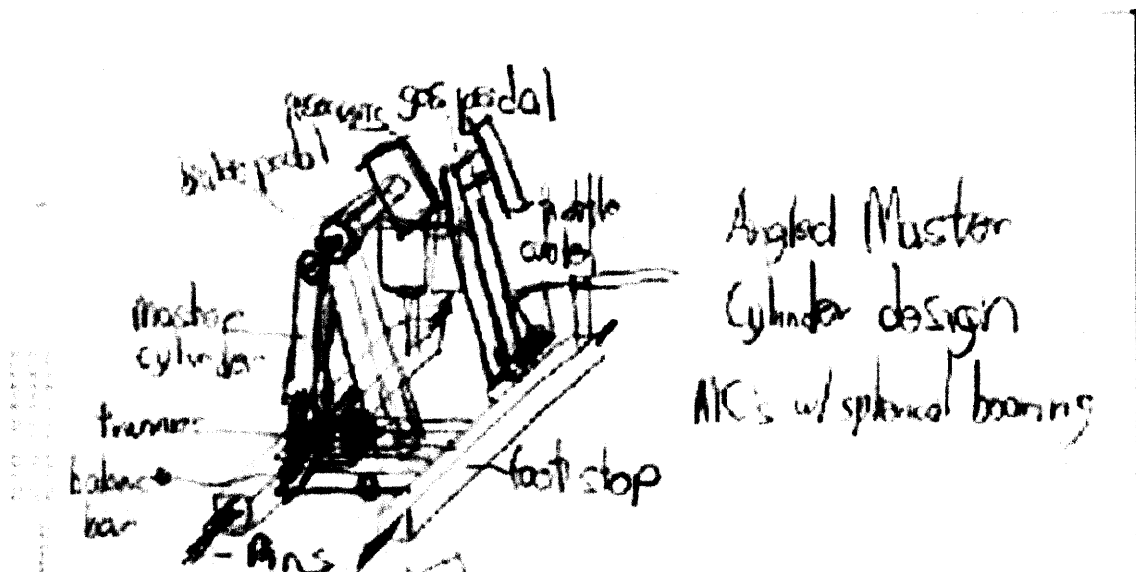

Figure 4: Angled Mounted Master Cylinders

The angled mounted master cylinders have many benefits. In this design, the master cylinder mounts upside down with the spherical bearing on the back of the cylinder attached to the brake pedal and the other side attached to a balance bar attached to the pedal box frame. The pedal box frame takes the forces acting mostly vertical rather than all horizontal. This enables the force to be distributed to the car's frame via either

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pins of just a flange on the pedal box frame in contact with the top of the square mounting tube on the car's frame. The frame can be made in one plane reducing the number of pieces used in manufacturing. The pedal box is very short and the heel stop can be integrated into the pedal box frame. The reduced length means the frame can be shortened and about 1.5 lbs can be saved. The brake pedal can weigh a lot less since the pedal is in pure tension because of the force balance. Overall if done right, it can be an extremely light weight and compact design that could gain a lot of points from the design judges.

There are several challenges with the design. First of all, the geometry is much more complex than in either of the other two designs. In order to calculate the pedal ratio, the change in master cylinder length and pedal angle will have to be determined though calculations. The spherical bearing mounted master cylinders are much more expensive than typical push type master cylinders. Bleeding can be a problem do to the orientation of the master cylinders. This can be remedied to some degree by mounting the master cylinder upside down. The reservoirs must mount remotely meaning that additional plumbing will be needed further adding to cost and complexity.

3.4 Clutch on Shifter

Each of the three proceeding designs can incorporate a clutch with a fairly equal degree of difficulty, so the decision of whether or not the clutch should be included in the design is independent of the proceeding master cylinder mounting decision. Removing the clutch from the pedal box and placing it on the shifter will decrease the complexity of the pedal box. The brake pedal and gas pedal will be able to be more spaced out. Drivers with larger feet won't have to move their feet from pedal to pedal making driving easier. It will decrease manufacturing time and will allow for better packaging.

The main problem with removing the clutch from the pedal box is that most drivers are used to a foot clutch. A secondary issue is that it increases the complexity of the shifter design. If the drivers get enough time in the car, they may be able to get used to the hand clutch.

4.0 Final Design

After careful consideration of the master cylinder and clutch positioning, it is decided that the best design in order to maximize points at the competition is the angled master cylinder mounting with a hand clutch. Even though the master cylinders are more 'expensive than the type used for the forward mounted master cylinders, the possible points gained in design and the weight reduction that will enhance performance is too good to pass up.

With the design, the frame is shorter in the front by 4 inches leading to a weight savings in the frame of 1.5 lbs and the pedal box weight is a mere 2.5 lbs. The total weight reduction in the car is four lbs over a traditional forward master cylinder mounting design. A solid model of the pedal box is in Figure 5.
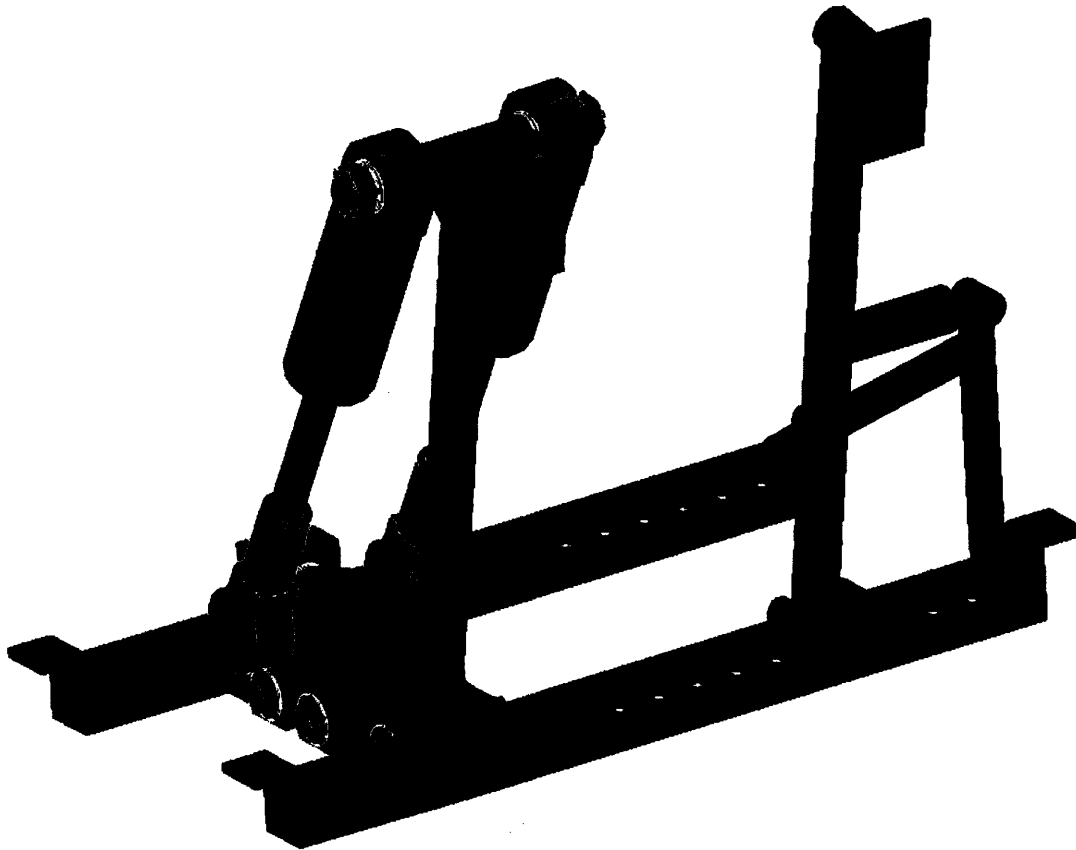
Figure 5: Solid Model of 2007 MIT Formula SAE Pedal Box

The design allows for new types of adjustability previously unseen throughout the competition. The design contains the typical moving frame design that allows driver of different sizes to move the pedal box to a comfortable driving position, but the

adjustability does not stop there. By mounting the balance bar on the pedal box frame, using a moveable trunnion design, the driver has a wide selection of pedal ratios and initial brake pedal angles to choose from. These extra degrees of adjustability should enable the team to gain many more points in the design part of the competition while increasing performance by tailoring the car to individual drivers needs.

The subsequent sections will explain the design rationale behind each of the components of the pedal box along with the analysis done to reach the design conclusions.

4.1 Brake Pedal Geometry

The first step to the design was to determine how the master cylinders and the brake pedal should interact. The two most important aspects of the brake pedal are the pedal ratio and the travel. There are also ergonomic considerations in the design as the drivers want the maximum travel to occur at about a 75 degree angle from the horizontal meaning that the initial brake pedal angle will be about 10 degrees towards the rear of the car. The pedal pad's midpoint must be about 7.5 inches in length as it is the average length of the male foot from heel to ball. Figure 6 shows the geometry of the brake pedal.
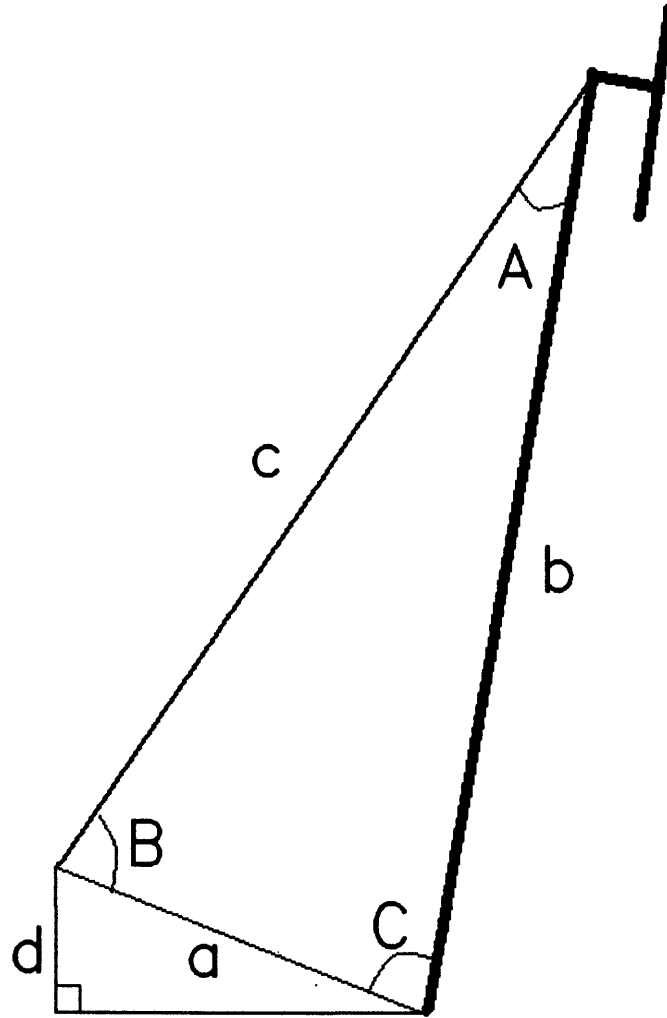
Figure 6: Brake Pedal Geometry

It is important to define all of the lengths and what distances can change before the equations governing the system are formulated. The brake pedal length, b, is a fixed length that must meet the requirements of the pedal pad touching the ball of the driver's feet. The master cylinder length, c, goes from the top of the brake pedal where the spherical bearings are mounted, to the balance bar located near angle B. This length changes as the brake pedal angle, C, changes. It can also be increased or decreased by changing the location on the push rod thread of the female rod end that attaches the push rod to balance bar. This can only be done when the system is not in use. The length between the brake pedal pivot and the balance bar, a, does not change in the system when the car is in use. With the moveable balance bar design, the length of a can be changed yielding different pedal ratios when desired.

4.1.1 Brake Pedal Geometry Theory

The goal of the geometry analysis is to give the driver a choice of pedal ratios in the range of 3:1 to 6:1. The travel should also range from 1.5 inches to 3 inches following that same pedal ratio pattern. To determine the pedal travel and the pedal ratio for the system, initial values for the length of the brake pedal, the distance between the pedal pivot and balance bar, and the initial brake pedal angle are input. The law of cosines determines the master cylinder length by

$$c = \sqrt{a^2 + b^2 - 2ab \cdot \cos(C)}. \tag{1}$$

Equation 1 calculates the master cylinder length as the driver causes the initial pedal angle to change. The pedal travel is equal to the arc length using

$$Pedal\_Travel = \left(C_{initial} - C_{finial}\right)b \tag{2}$$

with the initial and final pedal angles in radians. The pedal ratio at each given point along the path of the brake pedal equals the pedal travel divided by the change in master cylinder length,

$$Pedal\_Ratio = \frac{Pedal\_Travel}{\Delta c}. \tag{3}$$

The next step is to determine where the pedal stops which is the point at which all four wheels lock up and the input force required by the driver at the point. The force from a master cylinder that enters the pedal box is

$$F = \Delta c \cdot A \cdot P \tag{4}$$

where A is the cross-sectional area of the master cylinder and P is the pressure in the master cylinder at lock up.

The total force entering the pedal box frame from the master cylinders is

$$F_{total} = F_{front} + F_{rear}. \tag{5}$$

The input force required by the driver's foot is

$$F_{input} = \frac{F_{total}}{Pedal\_Ratio}. \tag{6}$$

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4.1.2 Brake Pedal Geometry Calculations

The calculations to determine the optimal pedal box geometry are done in Matlab. The inputs are the pedal length, initial pedal angle, and distance from the pedal pivot to the balance bar. The code simulates the pedal moving through an arc and computes pedal ratio and input force required. Figure 7 shows a wide range of pedal angles from the start at 90 degrees all the way to zero degrees.
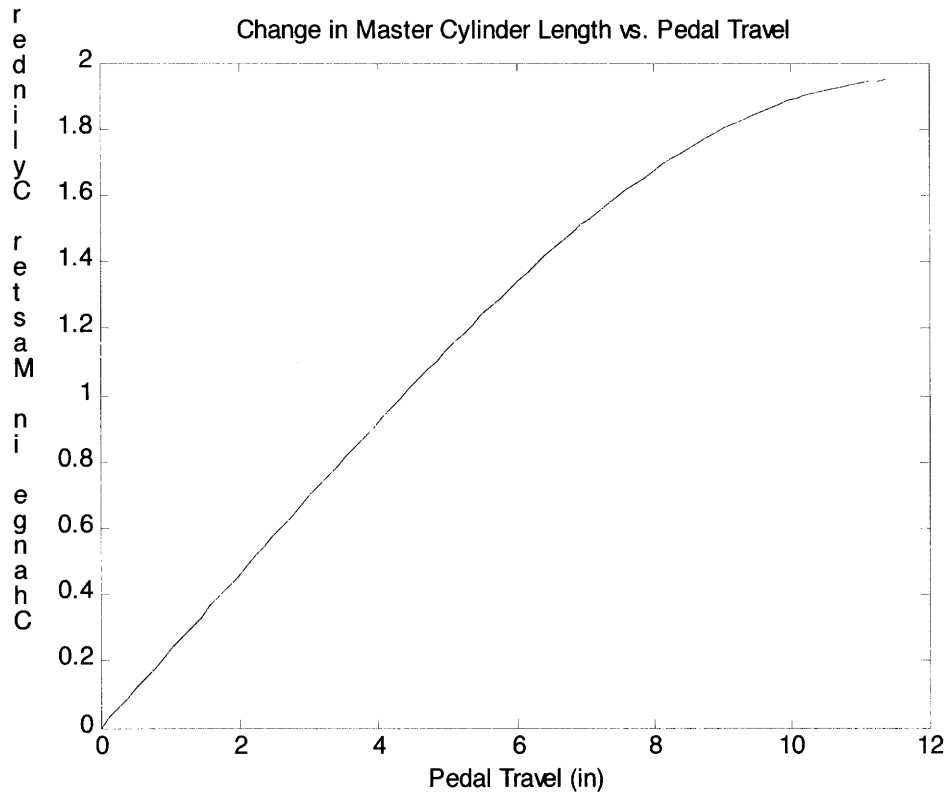
Figure 7: Change in Master Cylinder Length vs. Pedal Travel for 90 to 0 degrees

Because the use of the law of cosines, the master cylinder length varies with pedal travel according to a cosine wave. By choosing an initial pedal angle and other geometry, one can choose where on the curve to operate. Only a slight increase in pedal ratio as the driver presses down on the pedal can be beneficial to driver feel, so working in a region that is relatively linear is beneficial.

An initial angle of 10 degrees rearward of vertical, a pedal length of 7.5 inches, and a distance of 1.75 inches from the pedal pivot to the balance bar yields Figure 8.
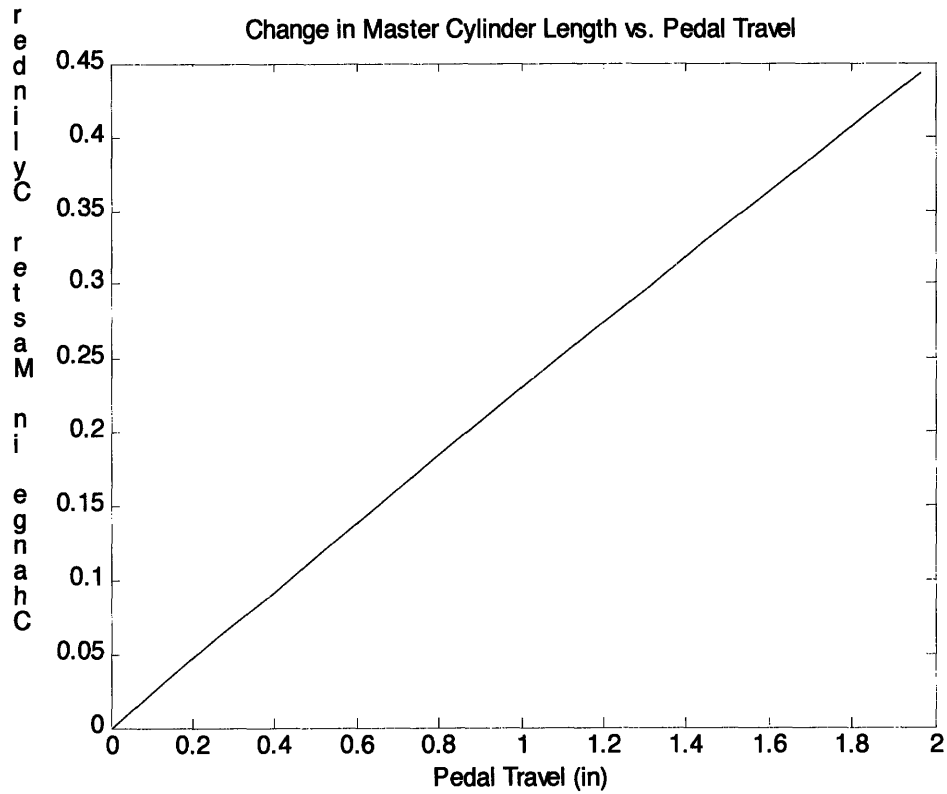
Figure 8: Change in Master Cylinder Length vs. Pedal Travel

Figure 8 shows the region of the graph that the pedal box works in. The region is relatively linear with only a slight increase in pedal ratio as the driver moves the pedal through the different angles. Next the input force is calculated at each angle to determine if the force required by the driver for lock-up is desirable. This is Figure 9.
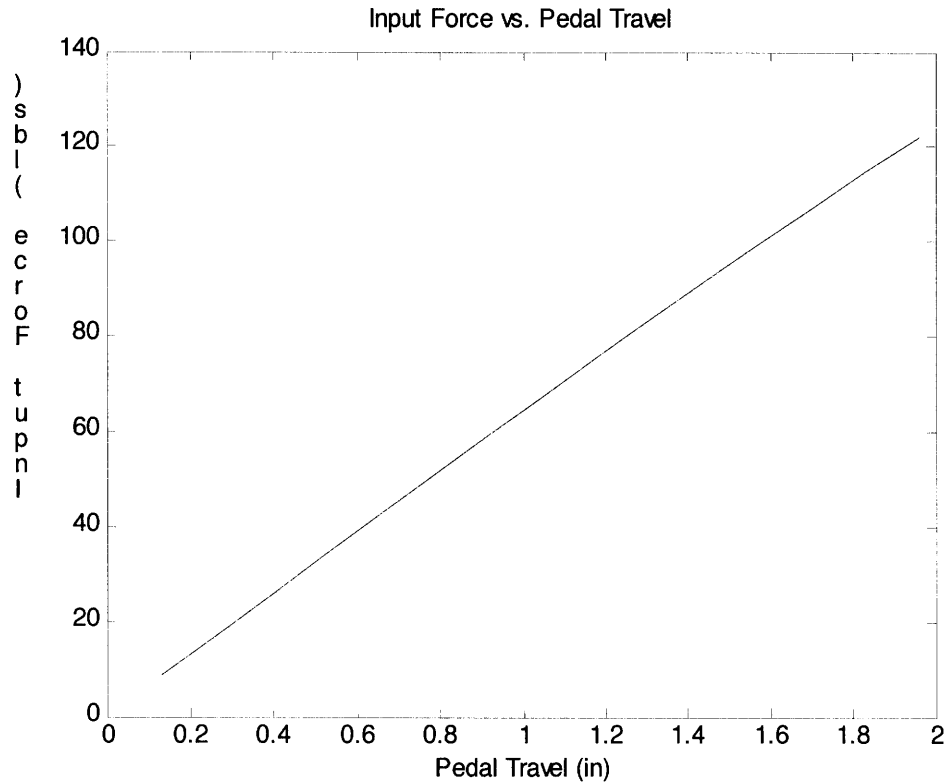
Figure 9: Input Force vs. Pedal Travel

It can be seen in Figure 9 that the input force required to lock up all four wheels is within the desired range of 100-120 lbs. The pedal ratio varies from 4.3 to 4.6 as it sweeps out its arc which is in line for the desired value. This pedal geometry works nicely for the large majority of drivers.

The next thing to determine is how moving the location of the balance bar will affect the pedal ratio and input force. To do this, the distance from the pedal pivot to the balance bar changes yielding Figure 10 and Figure 11.
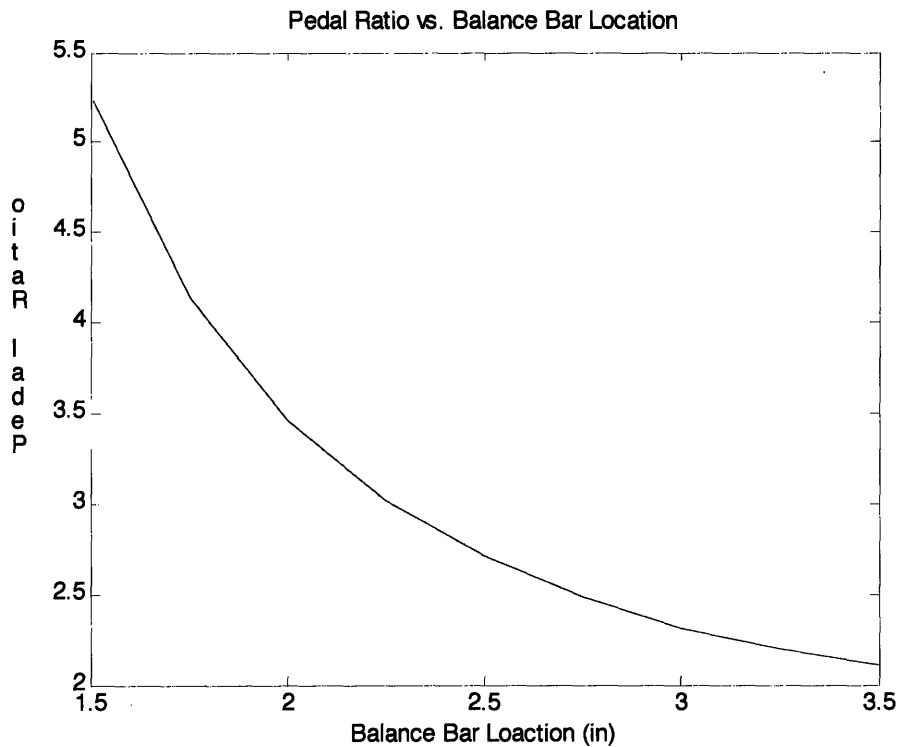
Figure 10: Pedal Ratio vs. Balance Bar Location

The pedal ratio used in Figure 10 is the pedal ratio measured when the angle, A, is at 55 degrees. The wheels may in fact lock before this angle meaning that the real final pedal ratio may be slightly less than the one presented in the graph. Figure 10 indicates that the pedal feel can be adjusted to an individual divers needs as the pedal ratio is the number one factor in how the brake pedal feels. While the initial pedal angle does change when the balance bar moves back, it does not change a significant amount as the initial master cylinder length can be adjusted as well; therefore, Figure 10 gives a good estimation of the pedal ratio as a function of the balance bar location
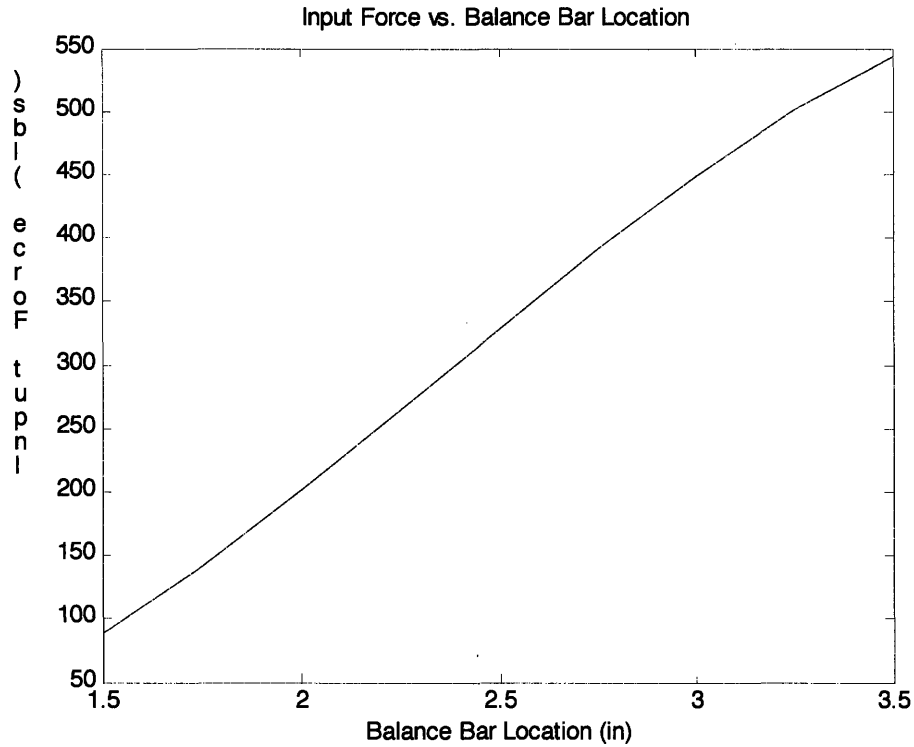
Figure 11: Input Force vs. Balance Bar Location

Figure 11 takes the same pedal angle that the pedal ratio in Figure 10 uses and determines the input force required to get the pedal to that position. Looking at the graph, it becomes apparent that at large offsets of the balance bar, the brake system should lock up at a much earlier pedal angle causing significantly less pedal travel. This indicates that as the balance bar location increases the input force from the driver needed to lock up the wheels increases, but since the pedal travel needed also decreases a quick impact from the driver when the balance bar location is far from the pedal pivot will cause the wheels to lock up quickly. This is very useful for passing the brake test at the competition and allows the drivers to have more feel during the endurance and autocross events where they need it for turns.

4.2 Master Cylinder Selection

The master cylinder selection played an intricate role in the design. Spherical bearing mounted master cylinders are much more expensive than traditional flange mounted master cylinders. The AP Racing spherical bearing mounted cylinders cost $675 and the Brembo ones cost $475 which is far too expensive to justify the cost. Tilton

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Racing recently came out with a spherical bearing mounted master cylinder very recently that only costs $290. The Tilton 77 series master cylinder is in Figure 12.
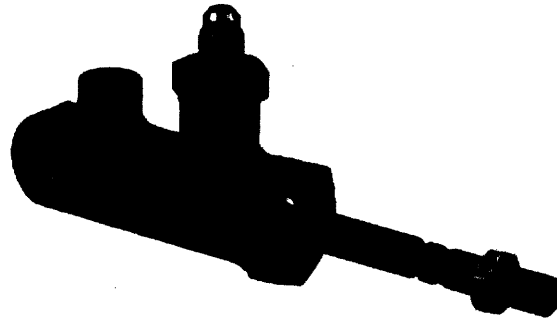
Figure 12: Tilton 77 Series Master Cylinder

The Tilton master cylinder only weighs 0.3 lbs compared to the 0.6 lbs of an AP Racing CP2623. Other master cylinders that teams run are oversized for the competition because of the low weights of the cars and the low speeds. The Tilton 77 Series only has 1 inch of total travel, but only needs to travel 0.4 inches to lock up. The body is very short which enables it to be part of the triangle with the break pedal. Mounting the master cylinders with the push rod down, allows for better bleeding since they are bled from the side with the spherical bearing.

From the brake caliper and disc data, the desired pressures in both the front and rear systems can be found. The brake system engineer provided a spreadsheet with the required pressures in the system. A copy of the spreadsheet is in Appendix B. It is desired for the input force into each master cylinder to be approximately the same so that both master cylinders travel nearly the same amount. This is especially important when mounting the cylinders at an angle since it is undesirable to have a large bending moment on the brake pedal. Also, the initial location of the master cylinders on the balance bar can be approximately the same distance from center allowing an equal force distribution on the balance bar and less of a change in the torque on the balance bar when the brake bias (front to rear brake ratio) needs to be changed. It is found from the spreadsheet in Appendix B that the front system needs a 5/8 inch bore master cylinder and the rear needs a ¾ inch bore master cylinder.

4.3 Balance Bar

The next driving component in the design of the pedal box is the balance bar. The balance bar connects the two master cylinders together and allows the brake bias which is the ratio between the force going to the front brakes to the force going to the rear brakes to be changed. The bore sizes for the master cylinders indicated that the master cylinder should initially be located the same distance from the center of the balance bar.

For the Tilton 77 Series master cylinders, Tilton recommends the balance bar in Figure 13.
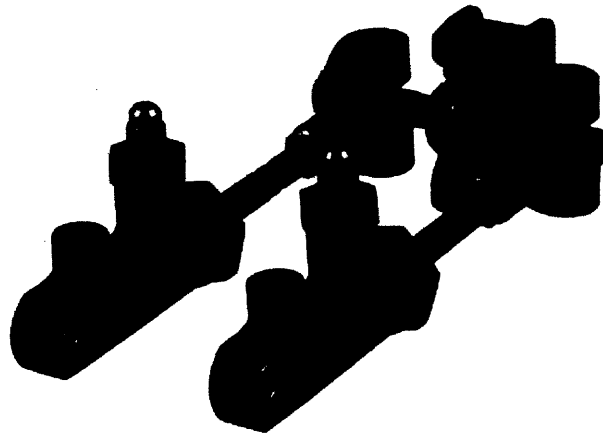
Note: Shown with optional 77-Series Master Cylinders

Figure 13: Tilton 72-280 Balance Bar for 77 Series Master Cylinders

While it works very well, the balance bar costs $675. Because the design is relatively simple, a similar style of balance bar will need to be built.

The best choice for the balance bare is a trunnion design similar to the one in Figure 11. Since the master cylinders are mounted on spherical bearings it is important to constrict some degrees of freedom in their motion. At the center of the balance bar is the main trunnion. The trunnion constricts movement in the x and z axes leaving it only to be able to rotate in the y plane. A shaft that the balance bar goes through rotates on two bearings pressed into a mount. The bearings must be pressed in after placing the shaft between the mounts since the shaft will not fit otherwise. The balance bar has threads on it so when the balance bar rotates the brake bias will adjust. The balance bar must therefore be able to rotate in the trunnion shaft. The female rod ends attached to the master cylinders must have threaded bearings that contain pins so that rotational motion is only in one plane. Alternatively, smaller trunnions similar to the ones in Figure 11 can be on the ends of the master cylinders to attach them to the balance bar.

The design for the balance bar and trunnion is in Figure 14.
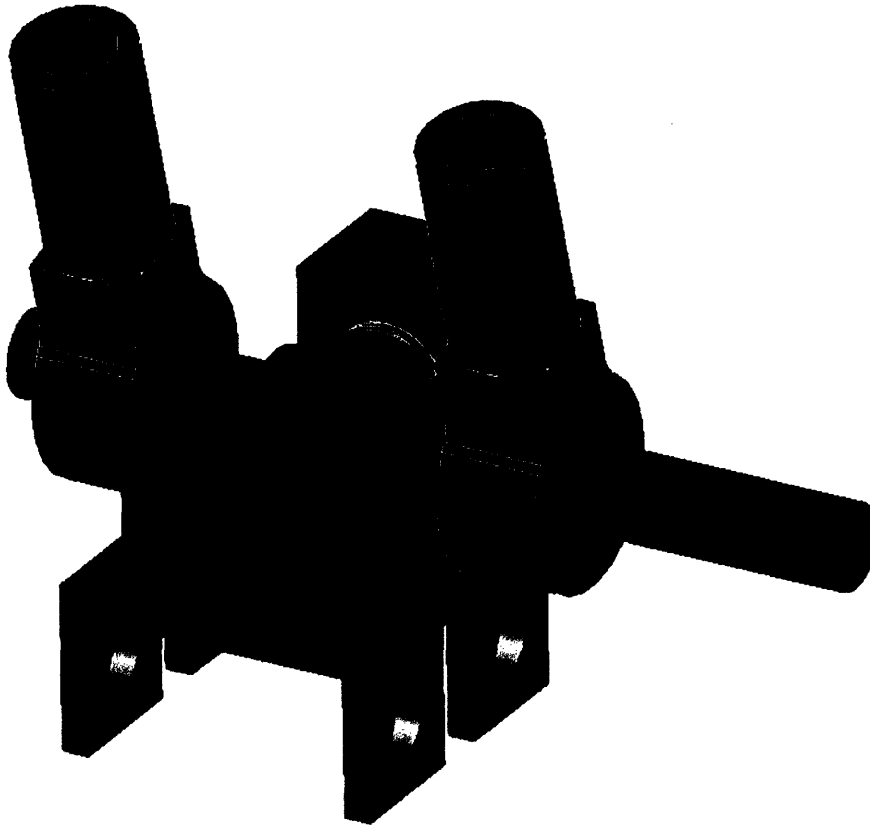
Figure 14: Solid Model of Balance Bar

The round stock constitutes the actual balance bar is made from 3/8 inch 4140 steel due to the need for a high yield strength. Each end of the bar contains right hand threads put on by a 3/8-24 die. The balance bar goes through the trunnion shaft. A hole reamed to 0.376 inches in the middle of the trunnion shaft allows the balance bar to rotate smoothly. To keep the balance bar from shifting side to side, self locking retaining rings are on each side of the hole through the trunnion shaft. The use of self locking retaining rings instead of retaining rings that require grooves keeps the balance bar at the same moment of inertia. Grooves cause a decreased moment of inertia against bending and allow for stress concentrations which can greatly weaken the balance bar. The balance bar is longer on one side since the remote adjustment for brake bias must connect to the balance bar in that location and it takes up part of the balance bar.

The trunnion mount is machined from a block of 6061 aluminum. The design calls for two needle bearings with 3/8 inch inner diameter pressed into the mount to hold the trunnion shaft in place. The trunnion shaft is made from 4130 steel bar. It is important

that the shaft can fit through a hole that is the outer diameter of the bearings as the shaft must be placed between the bearing holders before the bearings are pressed in. Otherwise it is impossible to get the shaft into the trunnion mount.

The trunnion mount must be able to connect in with the pedal box frame and be able to move when drivers change. To do this, four flanges located beneath the base of the trunnion mount enable bolts to go through whatever the trunnion mount is located on. Figure 15 shows the trunnion mounted on the pedal box frame.
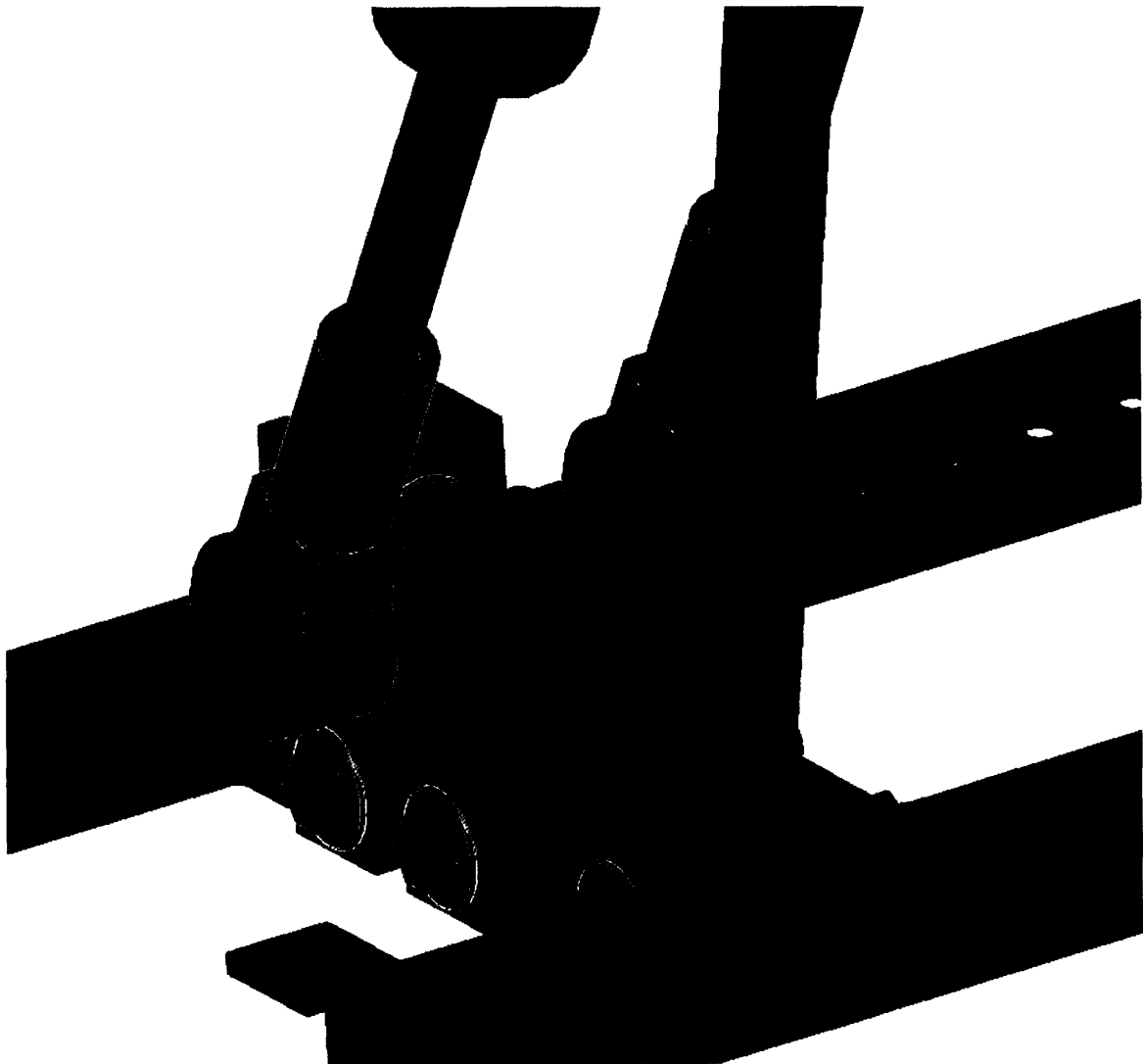
Figure 15: Balance Bar and Trunnion Mounted to Pedal Box Frame

The trunnion mount slides along a frame member and can be locked in place using the two horizontal bolts.

The female rod ends are a special kind of rod end that contains threading in the bearing. The threading allows the rod ends to be threaded onto the balance bar and when

the balance bar rotates, the location of the rod ends with respect to the center of the balance bar will change. The bearing at the end of the rod end contains a pin which restricts movement to only the one direction that is desired to move in. these rod ends come from an inexpensive AP Racing balance bar.

4.4 Pedal Box Frame

The pedal box frame design needs to accommodate the balance bar trunnion mount, the brake and throttle pedal, the throttle cable, the master cylinders, and plumbing. The key to the design is simplicity. Due to the way the forces travel in the pedal box, the brake pedal pulls up and towards the front of the car while the master cylinders push down and towards the front of the car. The attachments from the pedal box frame to the frame of the car must constrain the motion of the pedal box to the front of the vehicle as well as making it so the pedal box won't rock up and down due to the counteracting forces from the brake pedal and master cylinders. The solution for this is in Figure 16, the solid model of the pedal box frame.
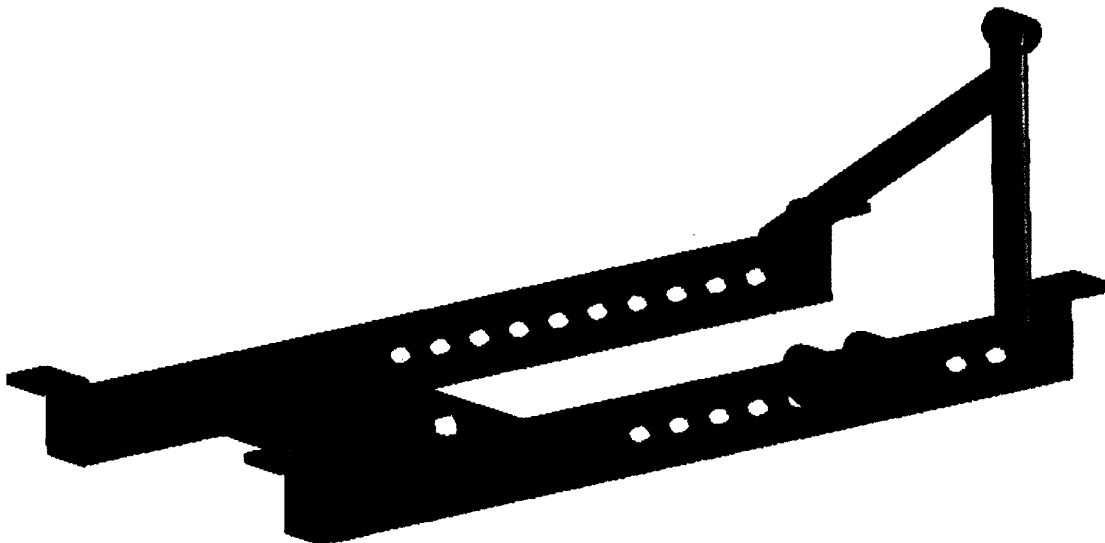
Figure 16: Solid Model of 2007 Pedal Box Frame

Two quick pins located towards the rear of the pedal box (rear of the car) will go through the car frame and attach into the pedal box frame. These pins restrain movement forward and aft inside the car. The four flanges on the top of the pedal box frame run along the top of the square frame rails. These restrain the motion down and make it so the pedal box cannot rotate around the two pins. This design is more beneficial than using

four pins as it is less expensive, requires less effort to move the pedal box, and is not over-constrained.

The pedal box frame is made from 4130 chromoly tubing and plate. The choice of material makes sense since it is very lightweight, strong, and, easy to manufacture since welding steel is much easier than aluminum. There are a total of four plates that are water jetted and then bent to shape, 4 5/8 inch square tubes and three 3/8 round tubes of 0.035 inch wall thickness. The two main beams of the pedal box frame run from left to right in the car. They are attached together in two different ways. The first way is by two 5/8 inch square tubes are machined and then welded together. Milling slots in these for the trunnion mount bolts as well as the brake pedal takes a minimal amount of time. On the right side of the vehicle, are the mounts for the throttle cable.

Finite Element Analysis (FEA) using Cosmosworks yielded strong results indicating that holes driller in certain locations would further reduce the weight without harming structural integrity. The minimum factor of safety in the design is 2.1. The entire pedal box frame weighs only 0.6 lbs while being very simple.

4.4 Brake Pedal

The brake pedal is a unique design since it must take a lot of force and since the master cylinders attach to the top of the pedal. The brake pedal design is in Figure 17.

Figure 17: Solid Model of 2007 Brake Pedal

The brake pedal is in almost pure tension with only a slight bending moment on it created by changing brake bias. This allows for a much lighter brake pedal by using ½ inch 4130 chromoly with a wall thickness of 0.035 inches as the pedal. The top of the pedal is a bar the must be turned down to meet the size of the spherical bearings on the master cylinders. Since the brake pedal pad takes the brunt of the attack, a couple pieces of water jetted steel are used as support. FEA analysis using Cosmosworks yielded a safety factor around three assuming minimal bending moment. The brake pedal only weights 0.25 lbs.

5.0 Manufacturing

The design is relatively easy to manufacture, due to the low part count. The pedal box frame is all in the same plane making jigging simple. All of the sheet metal parts are cut on a water jet to decrease the manufacturing time and increase part quality. The machining of the pedal box frame members is done by hand on a mill. The trunnion mount can be CNC milled from a block of aluminum and is the most complicated piece. The balance bar threading occurs on a lathe. Turning down the trunnion shaft occurs on the lathe and the drilling and reaming occurs on a mill or three axes drill press due to the need for precision. Pedals are very simple and can be manufactured using the lathe for the bearing pockets and grinding the tubes to fit. The completed pedal box is in Figure 18.
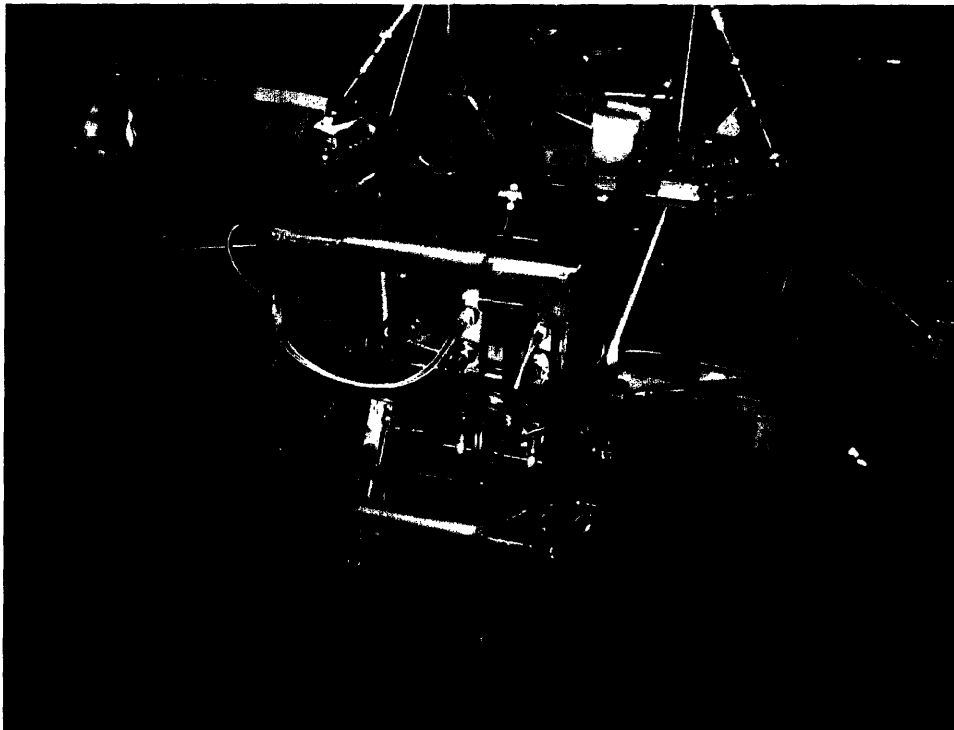
Figure 18: Completed Pedal Box

6.0 Cost Breakdown

An outline of the costs associated with the pedal box is in Appendix C. The cost breakdown is very important as a full cost report of every single component on the vehicle is sent before the competition starts. The cost report not only outlines all of the parts and materials used in the construction of the pedal box, but also a full process description of the pedal box. There are costs associated with manufacturing. For example an hour of labor costs $35. The total cost of the pedal box including master cylinders and reservoirs is $979.73 which is a little on the high side, but cost is not as important as design or performance.

7.0 Conclusion

The design of the 2007 MIT Formula SAE pedal box is innovative while being very practical. With a total weight savings to the car of 4 lbs and additional adjustability of being able to change the pedal ratio to match driver needs and driving conditions, the design will earn more points for the team at the design presentation and in the dynamic events.

8.0 Acknowledgements

Daniel Frey, for being the advisor for the Formula SAE team.

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Justin Negrete, for helping assemble all of the components.

Appendix A: Frame Safety Equivalency Form

While square tubing with the same wall thickness as a round tube clearly has a higher moment of inertia than the round tube, in the case where the square tube is drilled for mounting things such as a pedalbox, it should be verified that the drilled square tube has an equal or higher buckling strength than the undrilled round tube.
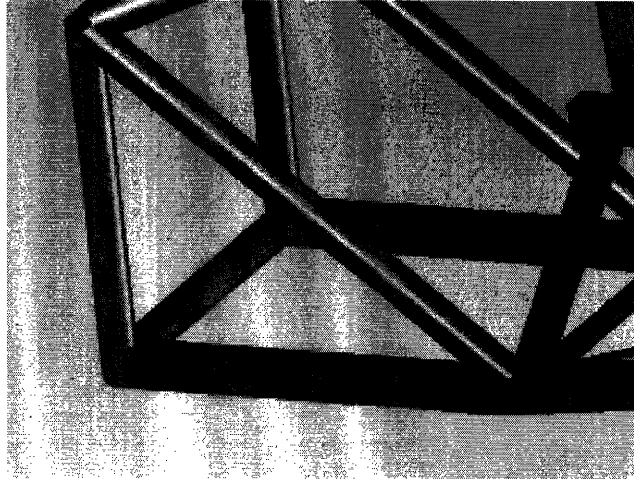
Here you can clearly see the area of interest: instead of 0.049 in. wall thickness round tubing, the bottom railing connected to the front bulkhead has been replaced with 0.049 in. wall thickness square tubing with 0.25 in. holes drilled at 2 in. intervals.

Length is assumed to be unchanged when comparing two cross sections. Therefore, the area moment of inertia can be used to compare buckling strength of beams of various cross sections.
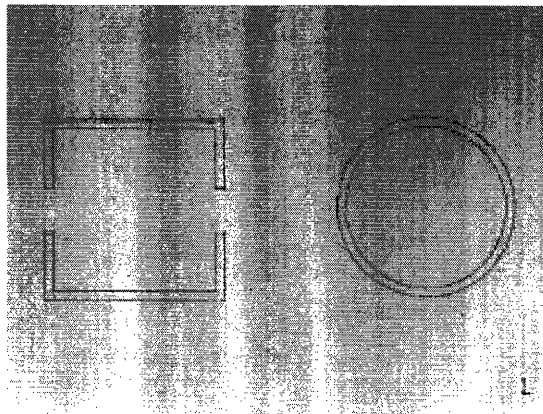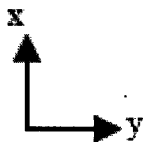
Here are the two cross sections we will be comparing. The minimum cross section for th square tubing is where the .25 in. holes are drilled out. This can be seen on the left. The right cross section is that of .049 in. wall thickness round tubing. The use of these two cross sections will give us a conservative comparison of the buckling strengths of the two tubes.

Using superposition, expressions for the moment of inertia of two channels can be built out of the familiar expression $I = BH^3/12$.

$$I_{xx} = \frac{W^4 - B^4 + B \cdot D^3 - W \cdot D^3}{12}$$

$$I_{yy} = \frac{W^4 - B^4 + D \cdot B^3 - D \cdot W^3}{12}$$

Where:
W is the width of the outer diameter
B is the width of the inner diameter
D is the diameter of the hole

The resulting area moments of inertia are:

$I_{xx} = 0.028 \text{ in}^4$
$I_{yy} = 0.023 \text{ in}^4$

For a round cross section, the moment of inertia is:

$$I = \frac{\pi(D^4 - d^4)}{64}$$

Where:
D is the outer diameter
d is the inner diameter

The resulting area moment of inertia is:

$I = 0.017 \text{ in}^4$

The alternative tubing has a greater area moment of inertia than the regular round tubing, even along its weakest axis. Since the square tubing is made from the same steel as the round tubing, its modulus of elasticity (E) is the same. Therefore, the buckling modulus (EI) of the alternative square tubing is greater than the required round tubing.

The higher moment of inertia also proves that the yield and ultimate strengths in bending are greater with the alternative tubing.

Since bending would be the primary form of deformation during a crash, the larger bending strength of the square tubing would also relate to a greater amount of energy dissipation as compared to the normal round tubing.

The uniaxial tensile strength is based on the cross sectional areas of the two profiles. Because of the identical wall thicknesses of the tubing, the only variation that would affect the cross sectional area is the perimeter of each respective profile. The approximate perimeter of the square tubing is 3.5", while the perimeter of the round tubing is 3.14". Since the perimeter of the square tubing is larger than the round tubing, it would have a larger uniaxial tensile strength.

Appendix B: Brake Pressure Spreadsheet

Brake spreadsheet

Wc	weight	698 lbs (wet)	Enter Values in Yellow Boxes
l	wheelbase	62 in	Green boxes are outputs
Ycg	center of gravity	9.5 in	
Xcg	cg from front axle	34.1 in	
rft	Rolling radius	10 in	
mu	grip of tires	1.5 coeff of friction	
muL	coeff of friction of pads	0.4 coeff of friction	
	Piston Diameter (mm)	32 mm	
Pd	Piston Diameter	▮ in	
Ap	caliper piston area	▮ sq in	
At	total piston per caliper	▮ sq in	
Rf	front rotor diameter	8 in	
Rr	rear rotor diameter	7 in	
	Pad Height (mm)	34.5 mm	
	pad height	▮ in	
re	front effective radius	▮ in	
	rear effective radius	▮ in	
Ff	Weight on Front tires	▮ lbs (wet)	
Fr	Weight on Rear tires	▮ lbs (wet)	
Fff	Friction Front	▮ lbs	
Ffr	Friction Rear	▮ lbs	
Tf	Brake torque front	▮ in-lbs	
Tr	Brake torque rear	▮ in-lbs	
Ap	Piston Area	▮ sq in	
N	Total number of pistons		
At	Total area of pistons	▮ sq in	
	Max Front Hydraulic Pressure	▮ psi	
	Max Rear Hydraulic Pressure	▮ psi	

master cylinder bore:
front 0.8200 in
rear 0.7600 in

Temperature			
	Max speed	70.00 mph	
KE	Kinetic energy	▮ feet-lbs	
Kf	KE to front brakes	▮ feet-lbs	for two brakes
Kr	KE to rear brakes	▮ feet-lbs	for two brakes

Area
front ▮ sq in
rear ▮ sq in

Force needed:
front ▮ lbs
rear

Fw	front rotor weight	1.9 lbs	
Nf	number of rotors	2	
Rw	rear rotor weight	1.2 lbs	
Nr	number of rotors	2	
Fwt	Total front rotor weight	3.8 lbs	
Rwt	Total rear rotor weight	2.4 lbs	
deltaTf	Temp rise in fronts	▮ degrees F	
DeltaTr	Temp rise in rears	▮ degrees F	

pedal ratio 6.2600 :1
▮ lbs
▮ lbs

60.0138

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Appendix C: Pedal Box Cost Report

Pedal Box BOM

Component	P/M	Description/Part #	Qty. We Paid	Retail Cost	Unit	Supplier	Total Retail Cost	Process Receipt	Ret. Receipt	Requires Custom Mfg. Process
Pedal Box / Pedals	M	Custom	1	-	$ 134.48	each	MIT	$ 134.48			Yes
Brake Master Cylinder	P	Tilton 77 Series, 5/8" bore front,	2	$ 286.38	$ 286.38	each	CV Products	$ 572.76			No
Balance Bar		3/4" bore rear	1	-	$ 125.15	each	MIT	$ 125.15	-		Yes
Brake Master Cylinder	M	Custom									
	P	AP Racing CP4706-13, Thin					Essex Parts				
Reservoir	P	Reservoir	2	$ 60.25	$ 60.25	each	Services	$ 120.50	-	-	No
Fasteners	P	Refer to Page 24	1	-	$ 1.84	set		$ 1.84	-	-	No
Assembly Cost	-	Cost to Assemble Brake System	1	-	35.00	hour	-	$ 35.00	-	-	No
		Total Cost of Brake System						$ 971.73			

Brake System Processes: Balance Bar

Material

Supplier	Part	Sub.	Qty.	Description	Volume	Weight	$/Unit	Cost
Aircraft Spruce		A	0.83	4140 Steel per Foot, 3/8" Solid Round		0.38	$ 0.60	$ 0.08
		B	1		1.5		$ 0.75	$ 1.14
Admiral Metals		C	0.25	4140 Steel per Foot, 5/8" Solid Hex		1.05	$ 0.75	$ 0.78
		D	2					$ 1.2
Behler Precision		E	2.00	Female Rod End, AGH 3/8" 3/8"-24			$ 17.75	$ 35.50
		F						

Process Labor

Sub	Qty	Amou	Description	Learning	Unit	$/Unit	Cost
A	1	1.00	Thread Balance Bar	1	Thread	$ 0.35	$ 0.35
B	1				Hour	$ 70.00	$ 11.95
B	2	1.00	Drill Hole for Bearing, 35/64"	1	Hole	$ 0.35	$ 0.70
B	2				Hole	$ 0.35	$ 0.70
C	1	1.00	Drill Hole for Balance Bar, 29/64"	1	Hole	$ 0.35	$ 0.35
C	1				Hole	$ 0.35	$ 0.35
C	1	0.25	Turn Down Trunion Ends to 3/8"	1	Hour	$ 35.00	$ 8.75
A - F					Hour	$ 35.00	$ 8.75

Total $ 125.15

Frame and Body Processes: Pedal Box/Pedals

Material

Supplier	Part	Sub	Qty	Description	Volume	Weight	$/Unit	Cost
West Aircraft Supply	A		0.67	4130 Steel per Foot, 3/8" x .035" Square		0.16	$ 0.50	$ 0.07
... Aircraft Supply	B		2.5	4130 Steel per Foot, ... x .035" Square			$ 0.50	$ 0.35
Aircraft Spruce	C		0.25	4130 Steel per Foot, 1/4" x .035" Round		0.04	$ 0.50	$ 0.01
Aircraft Spruce	D			4130 Steel per Foot, 3/8" x .035" Round			$ 0.50	$ 0.03
Aircraft Spruce	E		0.5	4130 Steel per Foot, 1/2" x .035" Round		0.17	$ 0.60	$ 0.06
Aircraft Spruce	F			4130 Steel per Foot, 1/4" Solid Round		0.17	$ 0.50	$ 0.08
Aircraft Spruce	G		0.50	4130 Steel per Foot, 1/2" Solid Round		0.67	$ 0.50	$ 0.20
Aircraft Spruce	H		1.00	4130 Steel, 6" x 6" x 1/16" Sheet		0.64	$ 0.50	$ 0.35
Aircraft Spruce	I		1.00	4130 Steel, 3" x 3" x 1/8" Sheet		0.32	$ 0.50	$ 0.10
Pegasus	J		2.00	Clevis Release Positive Locking Pin, 1/4" Dia. 1.25" Length			$ 14.75	$ 29.50
McMaster Carr	K		2.00	Snap-in Nylon Bearing, 1/4" Dia.			$ 1.70	$ 3.40

Process Labor

Sub	Qty	Amount	Description	Planning	Unit	$/Unit	Cost
A-C		2.00	Cut Throttle Pedal Tubes	1	inch	$ 0.40	$ 0.80
E-G		1.00	Cut Brake Pedal Tubes	1		$ 0.40	$ 0.40
B-D		7.00	Cut Pedal Box Frame Tubes	1	inch	$ 0.40	$ 2.80
F			Cut Back Pin to Hold Pedal Box	2		$ 0.40	$
G		0.10	Turn Down Master Cylinder Mount	1	hour	$ 35.00	$ 3.50
G			Thread ... Master Cylinder Mount, 9/16"-24	1		$ 0.35	$ 0.75
A		14	Drill Hole in Throttle Pedal Tubes, 1/4"	1	hole		$ 4.90
B			Drill Hole in Frame Tubes, 3/8"	1	hole	$ 0.35	$ 7.70
G		1.00	Drill Hole in Brake Pedal Tube, 3/8"	1	hole	$ 0.35	$ 0.35
I			... Frame ...	4		$ 70.00	$
H		0.00	Waterjet Pedal Pad	2		$ 70.00	$ 0.10
H			... Throttle Mounting Plate	1		$ 70.00	$
H		0.00	Waterjet Brake Pedal Guard	2		$ 70.00	$ 0.10
H			Waterjet Brake Pedal Tab	2		$ 70.00	$
H		0.00	Waterjet Throttle Cable Mount	1		$ 70.00	$ 0.10
A-E			...	1		$ 9.75	$ 12.00
B,D,H,I		32	Weld Pedal Box Frame	1	inch	$ 0.35	$ 11.20
A,C,F,H			... Throttle Pedal	1		$ 0.35	$ 1.75
E,G,H		20	Weld Brake Pedal	1	inch	$ 0.35	$ 7.00
A-K			Assembly	1		$	$
						Total	**$ ...**