Design of ¼ Scale Tractor

For ASABE Design Competition
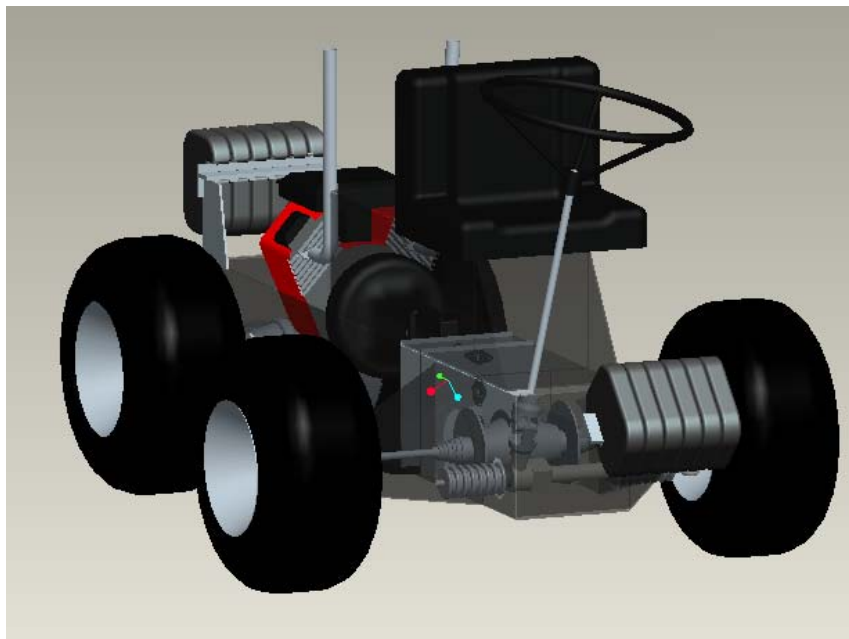
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1.0 - Introduction

1.1 -Acknowledgements

Designing and building a ¼ scale pulling tractor is quite an undertaking I would like to acknowledge the following people for there assistance with the McGill Pulling Team.

Dr. Robert Broughton – testing track construction and support
J.F. Grandmaitre – 2002-2003 Team Captain, for showing the ropes
Dr. Edward McKyes – For help with soil shear observations.
Sylvain Chabot and Pascal Normandeau – For past work on tires and lug configuration.
Dr. Samson Sotocinal – team advisor
Ray Cassidy – technical assistance
Samuel Price – 2004 team secretary
Nicolas Francoeur – 2004 team design chief

1.2 - Overall Competition

Each year the American Society of Agricultural and Biological Engineers hold a ¼ scale tractor student design competition in East Moline, Illinois. The objective of this project is to get students studying in Agricultural Engineering to apply skills learned in their courses to design and manufacture a ¼ scale tractor. The project has five main categories: Written Design Report (500pts), Team Presentation (500pts), Individual Design Judging (200 pts), Maneuverability and a Performance Competition (800pts). Through all of this the students involved acquire a strong sense of the professional design process, thus preparing them for a professional engineering career.


Figure 1. Example of 2004 McGill Pulling Team tractor in action

1.3 - Performance Competition

The actual tractor pull takes place on an East Moline clay track. There are four different weight classes (1000, 1250, 1500, 1750lbs). The original tractor must weigh in at 900 lbs including driver then ballast is added to achieve the desired weights.

When pulling with a four wheel drive tractor the optimum weight distribution over front and rear axles is 50/50, this provides equal downward pressure on all tires to minimize wheel slip.

There are two different types of pulls, an angled pull and a straight pull. When pulling the sled with the angled chain configuration there is a moment created about the rear axle causing the front wheels to lift of the ground, to counter act this ballast is added to the front of the tractor. When pulling the sled with a straight chain configuration there is no moment created about the rear axle therefore all ballast should be divided 50/50 over the front and rear axles for maximum pulling potential.
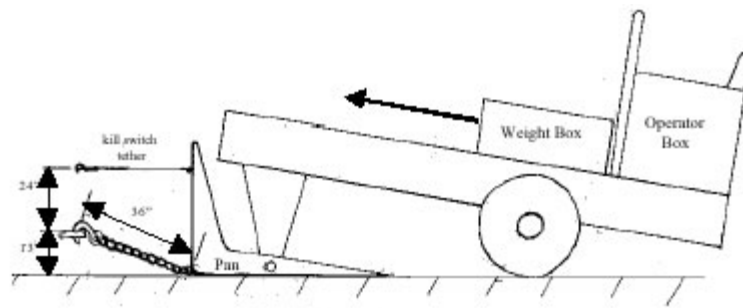
Figure 2. Angled chain sled configuration.
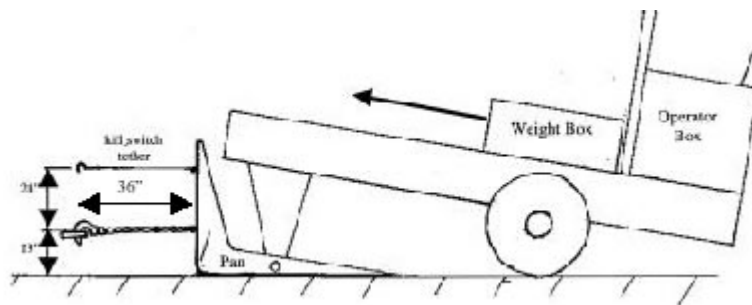
Figure 3. Straight chain sled configuration.

1.4 - Design Judging

Part of the point scoring for the competition is from design judging. This is done in three categories: Manufacturability, Serviceability and Safety. These categories are evaluated by three teams of Engineers who work in the manufacturing industries.

Manufacturability- Judges evaluate the ease of teams manufacturing processes by inspecting the amount of machining that has to be done to build the tractor.

Serviceability- Judges evaluate how easy it is to check tractor fluids and any other part of tractor that will require regular maintenance.

Safety- Judges evaluate how safe the tractor is to drive. This includes things like location of batteries with respect to the fuel tank, possibility of rollover and shielding and covers used to protect driver from drive train components.

1.5 - History of McGill Pulling Team - Problems and Accomplishments

Year 2000

- This was the first year McGill entered a tractor into the annual competition.
- Steel frame and covers.
- Poor steering and braking.
- Suzuki Samurai transmission and differential were used in combination with chain and sprocket assembly, proved to pull well.
- 2WD
- 20th overall

Year 2001

- Aluminum frame and covers were used to minimize weight.
- Poor steering and braking.
- CVT (continuously variable transmission) was used from a bombardier snow mobile allowing the right amount of torque to be transferred.
- Weight transfer ballast was used. This proved innovative but not effective.
- 14th overall

Year 2002

- Aluminum frame and covers.
- Poor steering and braking.
- 4WD, CVT was used again in combination with a gearbox with two output shafts to feed two bombardier differentials.
- 20th overall

Year 2003

- Aluminum frame and covers.
- Same drive train as 2002.
- Slightly improved steering team was able to complete the maneuverability portion of the competition.
- Improved braking from use of Pontiac firefly brake team passed brake test on first attempt also a first.
- 18th overall

Year 2004

- Steel frame was used as design judging from past years said aluminum is expensive and hard to weld making it not very manufacturable.
- Totally mechanical drive train; Suzuki Samurai clutch and 5 speed transmission was used to accommodate a new no CVT rule. Transmission fed a chain and sprocket assembly, which split power to front and rear axles, this proved hard to maintain, not as sound as the CVT.
- Improved steering by purchase of a Pontiac Firefly rack and pinion steering gearbox.
- Improved braking again by using Pontiac firefly brake piston and brakes on all four wheels.
- Design judging suggested a more easily manufacturable design which could be mass produced easily.
- 14th overall.

1.6 – Overview

With knowledge of how the competition is judged and proceeds along with knowledge of past designs and their problems and advancements I will be able to design a ¼ scale tractor that will be able to compete with the large American universities, and to improve on the 14th overall ranking, which is the highest McGill finish to date.

2.0 - Problem Statement

The McGill pulling team has competed in this competition five times. I have been a part of this team twice; 2003 (team member), 2004 (team captain). Each year the team spends many hours in the Macdonald Campus engineering shop constructing their tractor. This as I have experienced is very time consuming. A better option would be to use available design software, and manufacturing companies to minimize tedious shop hours.

3.0 - Objectives and Scope

To design a ¼ scale tractor using Pro Engineer and Autocad software;

- Increase manufacturability. Easily manufacturable tractors receive higher points in design judging, and are easier to repair.

- Design a sheet metal frame that can be bent to enclose all internal drive train components and points to attach all parts, so tractor can be pieced together like a kit.

- Design a new custom gearbox with an appropriate reduction ratio to transfer power from transmission to differentials.

4.0 - Methods

4.1 - Frame

By modeling desired parts in pro engineer a frame can be designed to accommodate them. The best way to do this is by designing a frame that can be bent from sheet metal. For the purpose of this project it is more cost effective than casting a frame which is how tractor frames are built in the tractor industry today. Casting requires making molds for the part to be molded; this is not cost effective if only building one part. Therefore a sheet metal frame serves the purpose well.

Figure 4. Example of bent sheet metal frame used by Kansas State University.

A bent sheet metal (1/8" steel) frame offers ample strength to resist bending while serving as a cover for all internal drive train components.

Bending Analysis in Frame

Data supplied by the ASAE from the previous competition showed that the tractor exerted a maximum pull force of 1.6 times its weight. Hoping to improve on this value, I assume a maximum pull force of 2.0 times the weight of the tractor. The tractor was hitched at a height of 0.33m above the ground. At maximum pull, the moment created by the pull about the tire/soil interface was

Max Bending Moment

$$M_0 = 0.33m * 793.8kg * 9.81m/s^2 * 2.0 \qquad \textit{Equation 1}$$
$$= 5139 \text{ Nm}$$

Where,
M_0 is the moment about the ground
0.33m is the moment arm of the hitch from the ground
793.8kg = 1750lbs was the tractor total mass during the pull
9. 81m/s^2 is the acceleration due to gravity

Second Moment of Area

$$\mathbf{I_{xx}=bd^3/12}$$ *Equation 2*
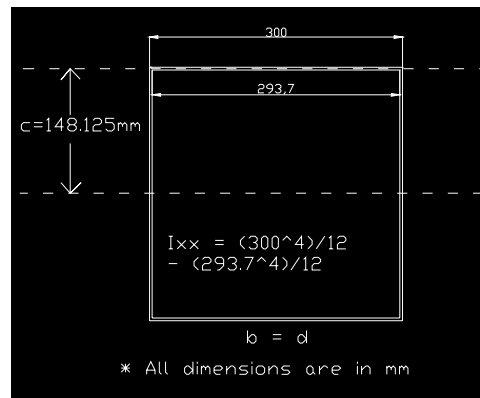$$= (300^4 -293.7^4)/12$$
$$= 54938823 \text{ mm}^4$$

Where,
I_{xx} = the second moment of area
b = width of the element
d = height of the element

** For hollow beams subtract the center area

Figure 5. Cross section of frame

Max. Bending Stress

$$\boldsymbol{\sigma_{MAX}=Mc/I_{xx}}$$ *Equation 3*
$$= (5139000\text{Nmm}*(148.125\text{mm}))/ 54938823 \text{ mm}^4$$
$$= 13.8 \text{ MPa}$$

Where,
M = 5139 Nm = 5139000 Nmm is the maximum bending moment
c=148.125mm is one half the height of the beam
I_{xx}=mm^4

** Since the strength of steel is 380 MPa, the frame will have little stress applied to it.

4.2 - Gearbox

The 2004 team chose to use a totally mechanical transmission which delivers maximum torque to drive tires.

The 2004 tractor did very well in the performance competition finishing 12th overall in a field of 30, despite being disqualified from one pull out of four. This means that the tractors gear ratio was very good. We noticed that the tractor would run out of power at the end of the pull and the engine would stall. This was from the gear ratio being slightly too high, with a lower geared tractor we believe our tractor could do even better. Therefore a gearbox can be designed with a lower gear ratio (higher reduction) to deliver more torque to the drive tires.

The 2006 design will be based on a simple drive train manufactured from readily-available materials and off-the-shelf parts. A Briggs and Stratton engine supplied by the ASAE will be coupled to a Suzuki Samurai five-speed transmission by a quick-disconnect. The output shaft will connect into a gearbox (which I am designing), which will have two output shafts that connect to drive shafts that provide power to the input shafts of the front and rear Bombardier differentials.

Torque calculations for Suzuki Samarui Gearbox with Briggs and Stratton16 Hp Vanguard twin Engine.

Engine Power

16 Hp = 11,931.2 N.m/s
=11.93 kW

Angular Velocity of Engine at Max. Torque

2400rpm * π/30 (rad/s)/rpm = 251.33 rad/s

Maximum Torque at Engine Output Shaft

(11,931.2 N.m/s)/ 251.33 rad/s = 47.47 N.m

Gear	Ratio	Torque after Gbx. (N.m)
1	3.652	173.36044
2	1.947	92.42409
3	1.423	67.54981
4	0.795	37.73865
R	3.466	164.53102

Table 1. Torque provided from transmission in all 5 speeds @ 2400rpm

Design of Gearbox Reduction Ratio based on Rimpull

The reduction through the drive train must be designed according to the maximum possible torque at the wheel. This is a function of soil conditions, tire contact area, and down force. The equation;

$$H_{max}=cA+N\tan\phi \quad \text{(McKyes, 2003)} \quad \textit{Equation 4}$$

is used to find the maximum rim pull given at the wheel
   c=soil cohesion, estimated at 70 kPa for East Moline soil
   A=area of tire/soil interface, approximately 0.076 m^2 fully loaded
   N=down force at one tire, assumed to be 25% of total tractor weight
   ϕ=soil shear angle=34 degrees

Given the maximum rim pull for each weight class, maximum torque at the wheel was calculated. Knowing the maximum engine torque from the Briggs and Stratton engine owner's manual, the total required reduction ratio through the drive train can be determined for each weight class.

Tractor Mass, Weight			Torque to Match Soil Shear	
			Rimpull H	Torque at shafts
(lbs)	(kg)	(N)	(N)	(N.m)
900.00	408.24	4004.81	5994.72	1979.46
1050.00	476.28	4672.28	6107.17	2016.59
1300.00	589.68	5784.72	6294.59	2078.48
1500.00	680.40	6674.68	6444.53	2127.98
1750.00	793.79	7787.13	6631.95	2189.87

Table 2. Torque from wheels in axles before reducing in differential.

	Reduction Ratio To Meet Soil Strength			
Gear	1	2	3	4
900 lbs	3.17	5.95	8.39	14.57
1050 lbs	3.23	6.06	8.55	14.84
1300 lbs	3.33	6.25	8.81	15.30
1500 lbs	3.41	6.40	9.02	15.66
1750 lbs	3.51	6.58	9.28	16.12

Table 3. Ratio required in designed gearbox for each gear

** These Ratios are for the gearbox between Suzuki Samarui transmission and differentials.

** Design for gear 3 (of Suzuki Transmission) to have a wider pulling range.

** The Rimpull formula is only accurate when tire lugs penetrate the soil completely. Since the pulling track is compacted by a steam roller after every pull it is difficult to have the lugs penetrate the soil to their maximum depth making the equation less accurate as we have seen in the past.
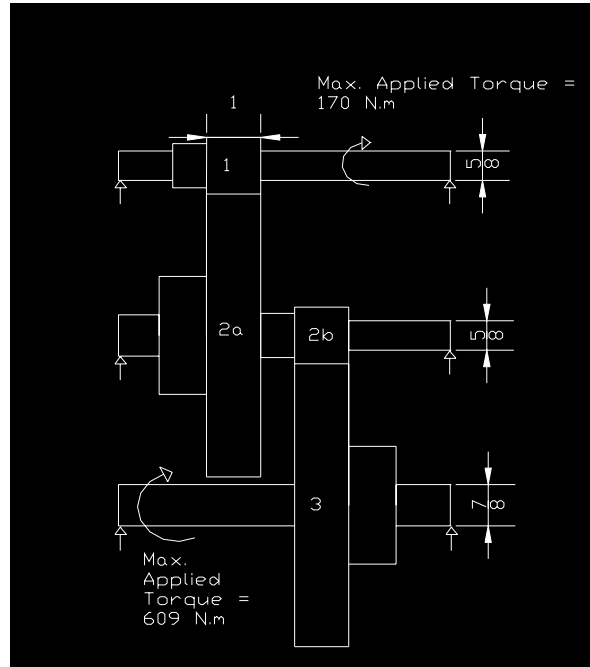

Figure 6. Schematic of gear configuration to achieve desired ratio.
Reduction Ratio = 60/12 x 60/12 = 25

Face Width	Gear	rpm	tooth/pitch	PD (")	V (ft/min)	L (lbf)	T (ft-lbf)	Max.T (N.m)
1 "	1	667	0.192	1.2	209.7048	2964.043	1778.43	*2411.22*
	2a	120.5	0.192	1.2	37.8852	3762.432	2257.46	*3060.70*
	2b	120.5	0.355	6	189.426	1124.235	3372.70	*4572.77*
	3	22.1	0.355	6	34.7412	1398.208	4194.62	*5687.15*
3/4"	1	667	0.192	1	174.754	2787.982	1393.99	1890.00
	2a	120.5	0.192	1	31.571	3420.043	1710.02	2318.48
	2b	120.5	0.355	5	157.855	1053.962	2634.90	3572.45
	3	22.1	0.355	5	28.951	1269.972	3174.93	4304.63
1/2"	1	667	0.192	0.75	131.0655	2626.304	984.86	1335.30
	2a	120.5	0.192	0.75	23.67825	3078.51	1154.44	1565.21
	2b	120.5	0.355	3.75	118.3913	988.3194	1853.10	2512.46
	3	22.1	0.355	3.75	21.71325	1142.006	2141.26	2903.16

Table 4. Calculations of max torque that can be applied to gears in gearbox, from Martin Sprocket and Gear Catalog 2001.

Gearbox shaft calculations

$$\tau_{max} = (16*T) / (\pi d^3) \hspace{4em} \textit{Equation 5}$$

Top shaft ; d=15.88 mm=5/8", Max. applied T=173,360 Nmm, $Sy_{(steel)}$= 380 MPa

$$\tau_{max} = (16*173360) / (\pi(15.88)^3)$$
$$= 220.5 \text{ MPa}$$
$$\text{S.F.}= 1.72$$

Bottom shaft ; d=22.23 mm=7/8", Max. applied T=609,000 Nmm, $Sy_{(steel)}$= 380 MPa

$$\tau_{max} = (16*609000) / (\pi(22.23)^3)$$
$$= 282.34 \text{MPa}$$
$$\text{S.F.}= 1.35$$

** These calculations calculate the maximum strength of the shafts used in the designed gearbox, the selected shaft size is strong enough to withstand the maximum applied torque.

5.0 – Results

I have found that the designed frame will be strong enough. By taking the bending diagrams in Appendix B to a sheetmetal shop, they will be able to have the frame manufactured.

I have chosen to use the gears with a face width of 1". This is so that the output shafts of the gearbox can clear the engine, and the driveshaft will not interfere with the engine. My calculations prove that a ½" face width gear will be strong enough.

6.0 - Cost Strategy

| Job	Hours	Cost/Hour (Junior Engineer Time)	Cost
Measuring and drawing parts	25	35$	875
Designing new frame	15	35$	525
Designing new gearbox	15	35$	525

Total Cost of Design = 1925$

7.0 - Conclusion

I feel that I have successfully taken experience and knowledge of past tractor competitions to design a tractor that will be able to compete quite readily with the tractors of the large American Universities. I was able to conceive a drive train that will provide ample torque to improve on the pulls of previous teams, also I have designed a easily manufacturable tractor compared to previous years.

8.0 – Appendix A

8.1 – Overall tractor design
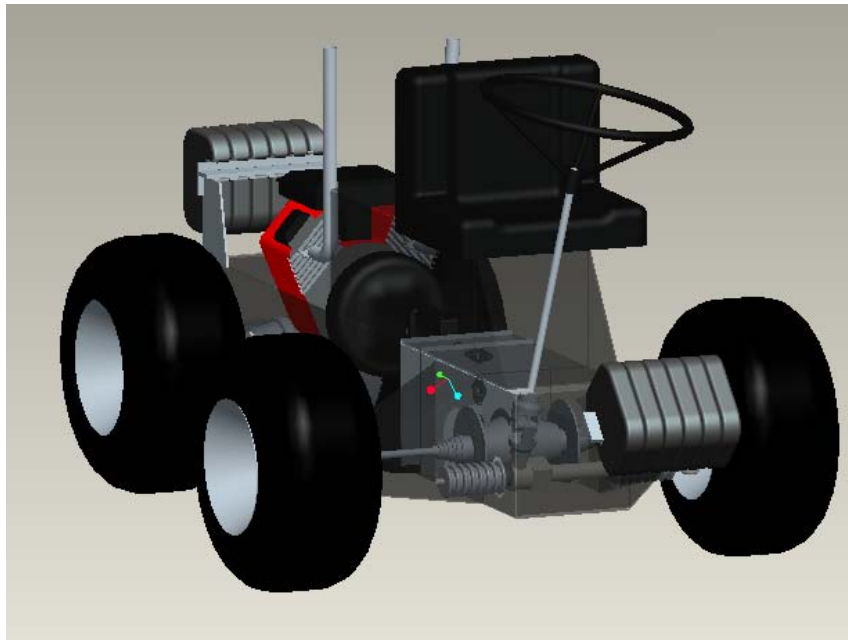
By placing the engine behind the driver we are able to place the driver over top of the front axle and leave a lot of open space around the front of the tractor, this will make it a lot easier to arrange brake, throttle and steering components.
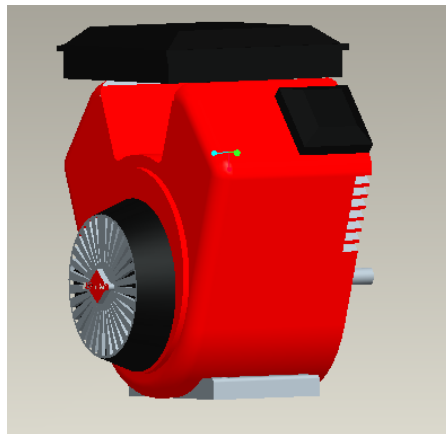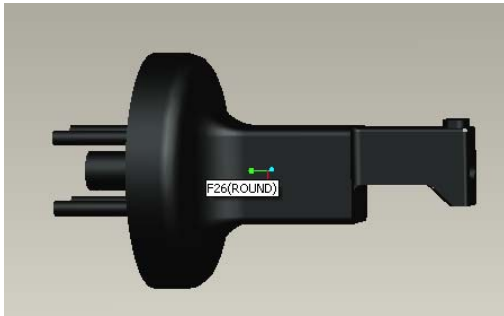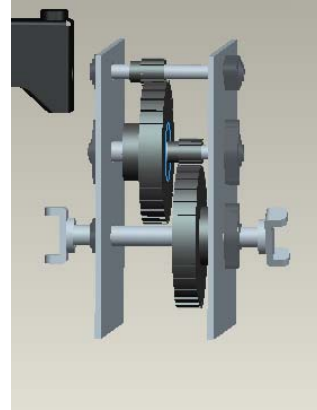
8.1.1 – Engine

Figure 7. 16 Hp Brigg's and Stratton Engine (modeled by Nicolas Francoeur)

8.1.2 – Drive Train

The drive train has mechanical Suzuki Samurai transmission and clutch assembly which attachs to the flywheel of the engine it is then coupled with a reducing gearbox which I have designed to have a reduction ratio of 25.

Figure 8. Suzuki transmission and clutch


Figure 9. Designed gearbox

The gearbox as shown has its bottom shaft exiting on both sides, this will provide power through universal jointed drive shafts to the front and rear axles.


Figure 10. Rear drive shaft

The front axle is composed of a Bombardier Outlander Viscolok differential (the differential lock is controlled by fluid as the wheels spin faster the fluid becomes less viscous causing the differential to lock both axles together) with shafts and hubs, this is the same axle assembly used in the 2004 pulling tractor. The hubs had to be machined to attach to a 5 lug rim, as the outlander only has 4 lugs.
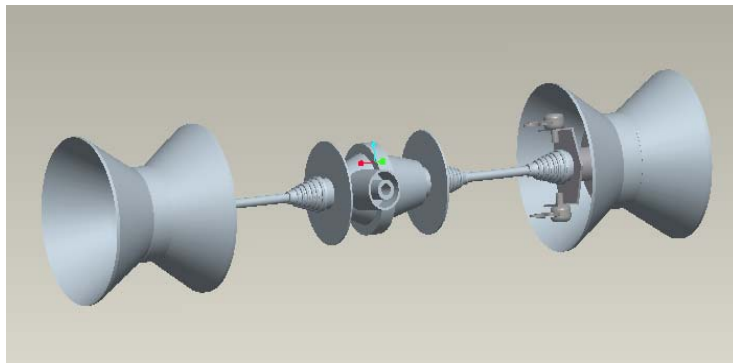
Figure 11. Front axle assembly

The rear axle is composed of a locked Bombardier ATV differential and axles. The axles need to have axle covers which are welded to the frame to hold the axle assembly in place
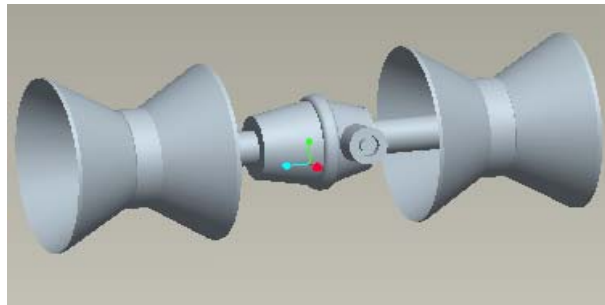
**Figure 12. Rear axle assembly**

8.1.3 – Steering system

The steering system used in 2004 proved to be the best solution to the previous steering problem other than using a power steering system which draws power from the engine. Although we were unable to compete in the maneuverability section due to problems in teching. I feel we would have done better than any previous McGill tractor, as we used a mechanical rack and pinion steering system from a Pontiac Firefly purchased from a scrap yard for 60$. This used with a steering wheel made the tractor much more maneuverable thus making it easier to control.
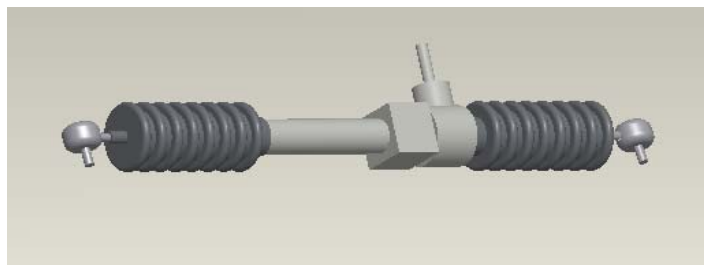
**Figure 13. Rack and pinion steering gearbox.**

8.1.4 – Braking system

In 2003 the purchase of several used Pontiac Firefly master cylinders made it possible to pass the brake test on the first attempt. In 2003 the cylinder fed brakes on rear axle only, in 2004 we also mounted brakes on our front axle, this proved to work well as we had no problems with the brake test. Therefore by using the same braking system as in 2004 we should have no problems with braking.
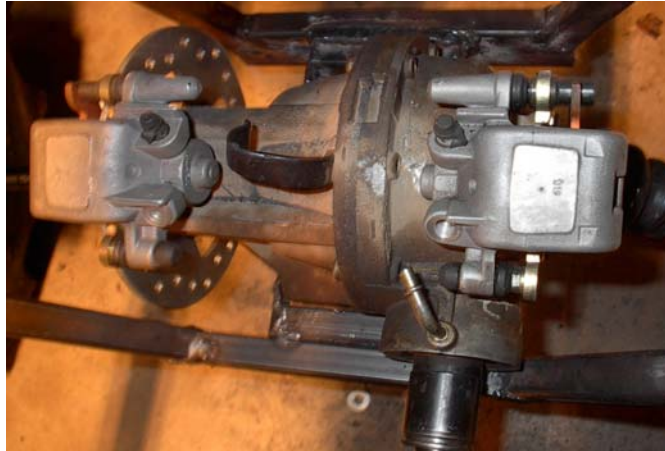
Figure 14. Bombardier Outlander Viscolok differential with two brake calipers.

8.1.5 – Frame
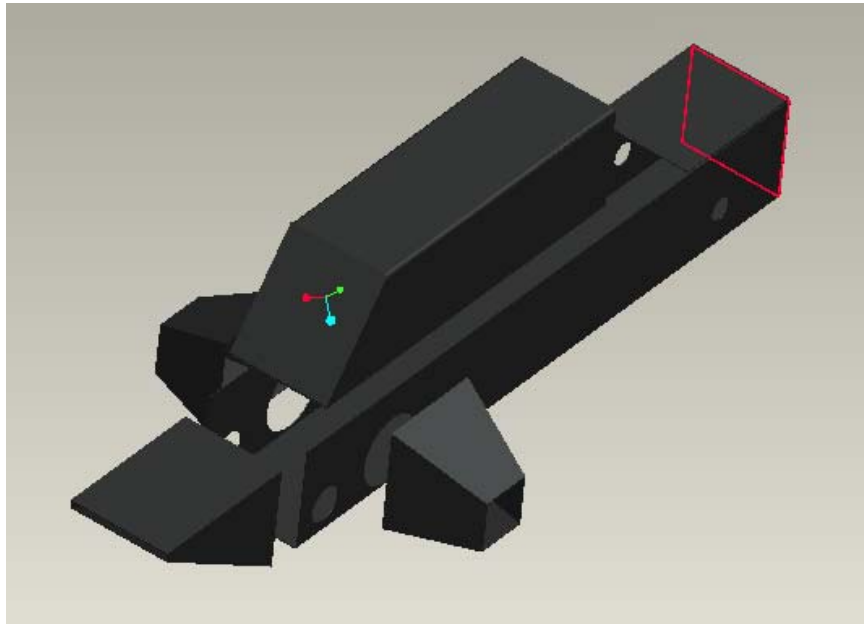
Figure 15. Frame assembly from modeled in Pro Engineer

In the past design judges have specified that aluminum is a poor material to use as a frame as it is soft, expensive and hard to weld, therefore the 2004 tractor used a steel

frame this was fine except for the manufacturability. A bent sheet metal frame looks good offers great strength and is more manufacturable, requiring only cutting punching and bending. This conceived frame will have to be pieced together. All parts should be welded together other than the top frame part which should be bolted for increased serviceability to internal components.

<u>Sheet metal manufacturing shops in Montreal:</u>

Werner Metals Inc., 149 Alston, Pointe Claire, 514-694-4922
Murphco Sheet Metal, 4955 Brock, Montreal, 514-937-3275
Manufacture Raymond Inc., 425 18th Avenue, Lachine, 514-634-5833
L H Manufacturing, 1790 55th Avenue, Lachine, 514-631-2193

8.1.6 – Ballast

Every previous tractor has used ½" steel plates as ballast, this is problematic as each plate is approximately 10 lbs and to ballast a tractor from 900lbs to 1750lbs it requires many plates. Previous teams have opted out of the higher weight classes due to insufficient ballast. Therefore I believe a just solution to this problem would be to use tractor weights, which weigh a lot more and are easier to handle.
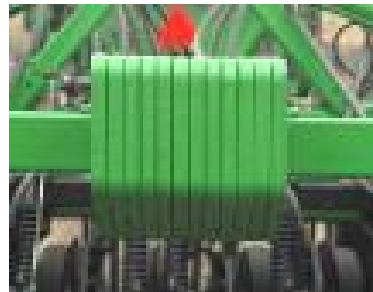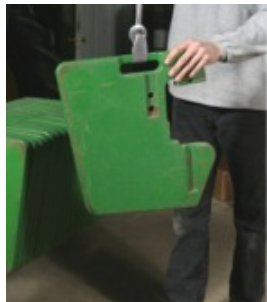
Figure 16, 17 – Examples of tractor weights

8.1.7 – Tires, Tread, and Rims

The McGill Pulling Team uses the same Firestone 26" x 12" Flotation tires as all other competitors. Past team members Sylvain Chabot and Pascal Normandeau (2002) published a report on the optimum profile of tires for the pulling competition. They concluded that given the heavy clay soil on the pulling track, two tire modifications increase the maximum traction.

- Sharpen the lugs as much as possible to bite into the packed clay
- Remove the ends of the lugs as they pass the tire midline. This decreases the interference between lugs as they contact the soil, and allows each lug to sink as far as possible into the soil.

Rims are five-bolt lightweight aluminum, which saves considerable weight and will allow the team to apply more of its weight in each class to moveable ballast for optimizing weight distribution.

Appendix B
Team Building Aspects

To have a successful tractor team there is several positions that need to be filled

Faculty Advisor/Supervisor (Sam Sotocinal) – The team needs an advisor preferably a professor in the department with experience with the design of machines and agricultural machinery. This person is to supervise the tractor project. Students are encouraged to make their design by themselves, but the advisor is there to answer questions and provide feedback that will help the project progress smoothly.

Team Captain – The team captain should be someone who has good leadership skills, and is good at motivating people. This should also be someone who is familiar with the competition rules and details to ensure that every thing runs smoothly. This individual should be a 3rd year student that has competed in the competition before.

Secretary – The team needs someone that is good with paperwork and that can keep documents organized. This individual should also have good word processing skills to prepare the written reports.

Sponsorship Leader / Treasurer – This position deals with making sponsorship proposals explaining the competition details. This individual should make contacts with companies and market the tractor team as a worthy cause for them to invest in. Also he should motivate 1st and 2nd year students to make contacts and to help with attaining enough money to pay for construction and travel costs associated with the competition.

Design Chief – This should be someone that is familiar with dimension criteria requirements of the competition and that can use this along with skills learned in courses such as design of machines and agricultural machinery to create a solid design. This individual should also use available software such as Pro Engineer and Autocad, to conceive a simple design, this individual should also be familiar with machine shops and there capabilities. All of this combined should be enough to design a tractor that is easily manufacturable.

Workers – To ensure that the team will continue there should be several 1st and 2nd year students to learn about the competition and help the sponsorship leader to get sponsors. These workers should also get some training in the machine shop to be familiar with the limits of welding and machining to enhance there conception of how the project progresses. These individuals should help with the construction of the tractor, by being part of this they will be motivated to continue in future years.

Appendix C

Frame bending diagrams