Design of a Differential Housing and Components of Differential Assembly

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Submitted in partial fulfillment of the requirements for the Senior Design Project

November 24, 2003

Problem Background

Each year the Society of Automotive Engineers (SAE) holds a competition in Pontiac, Michigan called Formula SAE (FSAE). Each year SAE releases a revised rulebook outlining the constraints of the upcoming year's competition. The racecar to be designed is an open-wheeled, mid-engine, rear-wheel drive racecar. The rules are intended to keep the event competitive and compel engineering students to be creative and innovative.

There are two separate aspects to the FSAE competition, the performance of the car and the design of the car. The performance of the car encompasses approximately 700 points and the design of the car encompasses the other 300. The performance aspect of the competition is made up of acceleration, skid pad, autocross, and endurance/fuel economy. These events test the quality of the manufacturing and tuning of the car, while the design events test the quality of design and cost analysis. The design aspect of the competition is made up of the judgment of the quality of the design, the cost report, and a sales presentation that each team must prepare. The goal of the design portion of the Formula SAE competition is to design a weekend-racer's racecar. FSAE competitors must design this car with the intention of producing 20,000 of racecars as cheaply as possible.

This year's Drexel FSAE team has approached us with a project to design a completely symmetrical differential assembly. This project requires an innovative design that is both light and strong.

Problem Statement

The differential housing and mounting design for an open wheeled formula race car is significantly different and more complicated then that of standard road going vehicle. A formula racecar is based off of a motorcycle engine/transmission, which normally uses a chain driven wheel. On a formula car, the chain does not drive the wheels directly. The chain drives an automotive-based differential, which in turn drives the wheels. This is where some of the issues become evident. On most of the cars sold today, the axis of rotation of the input (driveshaft) and output (axles) is perpendicular. On a motorcycle, the axis of rotation of the input (sprocket/chain) and output (axles) is parallel. This causes some packaging and design problems since, a motorcycle chain drive, and automotive differential must be used.

Another problem with the combination of motorcycle chain drive, and automotive differential is the differential housing. A differential must be lubricated; therefore it must be located in a sealed housing. On a normal vehicle the differential is mounted in the transmission or in its own stationary housing. Because of weight and packaging concerns, a formula car cannot afford to have a heavy stationary housing. To contain the oil, a housing which rotates with the differential must be integrated into the total design.

The problem of brake rotor placement is another issue to be dealt with in a formula car. On a normal vehicle the brakes are located on the outer axle side. Locating the brakes at the wheels increases the up sprung weight of the suspension considerably. Reducing the up sprung weight on a formula car is very important to suspension tuning. Reducing the up sprung weight of the rear wheels in very crucial because of the extra weight of the axles compared to the non-powered front wheels. Using a single brake rotor attached directly to the differential, in a similar manner as the sprocket, is the cheapest and easiest to package solution. Unfortunately this also complicates the differential housing design.

Current and past Drexel Formula SAE racecars have used chain driven Torsen differentials. These designs have the differential mounted to the rear chassis of the racecar. The rear chassis is connected to 4 existing mounts on the rear of the transmission. The rear suspension is also attached to the rear chassis. Because of the torque applied to the differential the rear chassis is stressed causing possible deflection in the chassis. These deflections would cause unexpected changes in geometry resulting in decreased traction. The current design also has the differential located off center, this means that the axle on one side is shorter then the other (Figure 1 Appendix A-2). This offset is in detriment to the optimal vehicle center of gravity.

The main design goals of this project are:

- To design and fabricate a symmetric differential assembly for a chain driven race car utilizing a Torsen style differential.
- The design will mount directly to the transmission, independent of the rear chassis to allow changes in wheelbase, track, suspension geometry, and redesign on the rear chassis for future formula racecars.

- The design will have to reduce rotational weight and improve adjustability, serviceability, cost, reliability, and ease of manufacture.
- To evaluate brake rotor size and sprocket gear ratio and change as needed.
- To create a differential rebuild manual with Bill of Material (BOM) to be used by future Formula SAE teams.

Constraints on the Design

The differential assembly to be designed must satisfy the following criteria:

- All components of the assembly must be as light as possible without jeopardizing structural integrity. This will require careful, precise calculations.
- The packaging of the differential housing must fit into the rear chassis of the car. The rear chassis is dimensioned very tightly.
- The components of this assembly must be able to handle the torque through the sprocket. This toque is yet to be calculated.

Methods of Solution

Upon evaluating the problem at hand, it can be seen that there are a few solutions that could be pursued. Perhaps the simplest solution, although it does not clearly correct the problem, is to do nothing. It is possible to use the differential and housing from a previous year, however, all previous years have incorporated different length axles. This will not solve the problems at hand. Another solution to our problem would be to incorporate a spool instead of the proposed differential. This is a feasible design; however, it will drastically reduce our competitiveness because of the loss of cornering maneuverability. The reason we are attempting to create equal length axles is to better integrate the differential into the car. By incorporating our design into the racecar framework, we are able to move the differential closer to the engine, thus moving the center of gravity forward. Our design will allow for greater stability, and will shorten the total wheelbase of the car significantly. It is obvious that in order to create equal length axles, we must center the differential between the rear tires. This is not an easy task to achieve. It will be challenging for the team because we need to make some adjustments to the differential housing itself. This is necessary because it is the housing in which power from the sprocket it transmitted through. The housing will basically be a tube that will have an end-cap on each end. Each end-cap will connect the surrounding tube to the differential. The opposing ends of each end-cap will be connected to either the sprocket or the brake rotor. Adjustments in centering of the differential will be made with said end-caps. It is very likely that one end-cap will be longer than the other because of the contours of the transmission. It will be challenging for our team to create different length end-caps without compromising the strength of the differential. We plan to incorporate a design that will reduce the shear stress on the longer end-cap.

Our differential housing assembly will be supported using two pillow mounts, complete with bearings, which will be attached to a bulkhead using bolts. This bulkhead will mount directly to the engine/transmission mounts. This mounting system will greatly increase the adjustability of the differential in comparison with previous years, because of the bulkhead and pillow mount design. The adjustments can be easily made using shims between the bulkhead and the pillow mount. Other possibilities that have been rejected by our team have included a mounting system in which the differential is mounted to the rear chassis of the racecar. This is not a desirable situation because it places unnecessary stress on the rear suspension. By incorporating our design, we intent to stress the engine and transmission only. This will create stability between the driving force (i.e.: the engine/transmission) and the driven part (i.e.: the differential and axles). In Figure 1 (Appendix A-2) shows a very simplified version of our conceptual design.

To perform our design, we intend to use a computer modeling program to create 3-D solid model representations. This method allows us to physically see how each part will interact with the others. We can see how our designs will fit together, and it allows us to foresee and complications we may encounter. Our computerized assemblies will include a bulkhead, two pillow mounts, two end-caps, two stub shafts, two axles, differential housing, and the differential. Our design is limited by a few constrains. We must keep our total design size within the constraints of the rear suspension chassis. This chassis is designed specifically to enclose the differential and is already completed. Therefore, we must create a design that can be placed inside of this rear suspension chassis. Another important constraint we must adhere to is the size and shape of the Torsen differential. Our design must house the Torsen differential, thus, we must create a design that will encompass it and adhere to all of its measurements. Other constrains we are limited by are bearing sizes, seal sizes, axle lengths, and material selection. A final consideration for our design is safety. The design of the housing will also help to encase any parts that could possible exit the differential. Because our differential will be housed behind the engine and transmission, if the differential were to fail and disassemble, pieces will not be able to injure the driver because of the engine's protection. This provides the driver with a second defense against the worst case scenario.

Once our solid model assemblies have been created, we intend to use the computer to assist us in performing finite element analyses (FEA) on each of our parts. We will input forces applied by the engine, weight, and the tires. Once preliminary FEA has been performed, and we are sure that each part has been designed to handle the required loads, we will attempt to eliminate material on parts where this is feasible (i.e.: the sprocket, brake rotor, and end-caps). We will again perform a FEA to ensure that our changes have not compromised the strength of the overall assembly. This final FEA will be our method of testing our computer model. After each part has been created, we plan to put the assembly through a "real life" test by implementing it onto the car.

We will be hand machining and lathing most of our parts; however we may choose to use CNC machining. Using a CNC machining method, we can eliminate errors and allow for tighter tolerance constraints. We plan to utilize the Drexel University Machine Shop and the Drexel Machinists' expertise in completing our manufacturing. We want to simplify our machining to help to keep our costs to a minimum.

Alternative Solutions

There a feasibly five alternate solutions to the one we are proposing. They are the following:

1) Open differential
2) Clutch style limited slip differential
3) Viscous coupling style differential
4) Spool and axle
5) Do nothing at all

The open differential is not efficient for racing because the driver loses some control during turns. This is due to the fact that the open differential transfers all of the torque to one side when the car is cornering.

Secondly there is a clutch style limited slip differential that has the capabilities of transferring torque from the wheel that isn't effectively transferring the torque to the ground, to the wheel getting more traction. This is a good differential but has disadvantages in comparison with the Torsen limited-slip differential. The clutch style doesn't transfer torque as efficiently between the inside and outside wheels, which makes the Torsen the better choice.

Thirdly we could use a viscous coupling differential. This system is usually found on four wheel drive cars. It uses circular plates, closely packed together encased in a housing that is filled with a viscous fluid. When the one set of wheels changes speed the other set senses it by trying to play catch up in this differential. Because of the fluid inside, both plates will try and move at the same speed, and if not one will be pulled by the other. This transfers the torque from the set of wheels that slip to the other that have traction. This alternative has no advantages in the racing environment, and therefore it would not prove useful for our purposes.

The fourth alternative is a spool design that takes the power right from the engine and puts it through the chain, to the spool which is attached to the axle. This differential applies exactly the same amount of torque to each wheel. This is very inefficient when going around a turn because one wheel tends to get more traction and thus could use more torque to pull through the turn. There are major problems with this design because whenever the car enters a turn the inner wheel is going to cover less distance then the outer wheel. Therefore if a spool were implemented there would be a braking effect on one of the wheels. Since the wheels can't spin at different rates one would be holding the other back, this is often seen and heard as chirping. Axles have been found to brake because of the torque applied by each wheel struggling to spin at it's own pace when going around turns. When exiting a turn, this differential will delay acceleration because of the loss of traction during the turn. The spool is a cheap solution, but the losses are too great to justify this alternative.

Lastly, we could do nothing at all. This wouldn't option would be cost effective; however, it would not be useful in eliminating some of the problems of teams in the past.

Project management

The required design, analysis, and testing tasks were split between two sub-teams. The first team, the integration team, will integrate the differential system into the car. This team will work with the chassis integration parts. These parts include all mounting brackets, brake caliper mount, brake rotor, and sprocket. The second team, the differential team, will work with all the remaining moving parts, including the differential housing, end-caps, stub shafts, axles, and bearing size. The differential team has some crucial deliverables in order to support the integration team. These deliverables include: the outer diameter size of the large bearing the differential is mounted to, and the bolt pattern for the brake rotor and sprocket mounting. The integration team will use these deliverables to design their mounting parts. The choice to split the team was done so the differential team does not need to concern themselves with integrating their design into the chassis. Please Refer to Appendix A-3 for Project Gantt Chart.

Economic Analysis

For a detailed explanation of drive train budget see Appendix A-1. After viewing the budget, one can see that we are under the assumption that every part has a price associated not only with the cost of the material itself but also with the cost of assembling. It would be unwise to be inconsiderate of assembly costs. With the assistance of the machinists in the Hess Laboratory machine shop, each part can be machined properly, provided a good set of drawings has been submitted. We plan to take full advantage of the Hess Laboratory with its CNC software and computer aided drawing technology. Some costs which include machinery costs, and computer aided drawing programs are not in our budget because they have already been acquired by Drexel University for our use.

Even with our current purchasing and manufacturing plan, there will be unforeseen costs. These may be small but must be taken into account. These costs may include travel, parts that we may have neglected, or any last minute changes that become necessary. We have included a 10% contingency to our total cost to account for any of these unforeseen costs.

Considerations for Societal, Environmental or Ethical Impacts

Our design has very little ethical or environmental impact. Because of cost, and concern for the environment, we plan to keep waste to a minimum; however, most of our waste from machining can be easily recycled. As for societal impact, we estimate that our design will improve on the competitive merit of the FSAE racecar. We hope that future drive train teams will learn from our analyses and improve our designs.

Appendix A-1 - Budget

Item	Amount	Cost/item	Total Cost
Stub Shafts 3 1/2"dia. x 1' (Annealled Steel Rod)*	2	$70.22	$140.44
Stub Shafts Total			**$140.44**
Pillow Block Mounts (Al 6061)			
Pillow Block, 2' x 1' x1" (Metal Supermarket quote)	1	$80.00	$80.00
Bearing (V groove) Free from SKF	2		$0.00
Pillow Block Mounts Total			**$80.00**
Sprocket (SprocketsUSA.com)	1	$40.00	$40.00
Sprocket Total			**$40.00**
Differential End Caps (cover) 3 1/2"dia. x 1' (Al 4140)*	2	$70.22	$140.44
Needle roller bearings with lip seal (free form SKF)	2		$0.00
Differential End Caps Total			**$140.44**
Differential Cover			
Center Differential Cover 4"dia. x 1' (Al 4140)*	1	$90.00	$90.00
O-ring Seals*	2	$2.20	$4.40
Differential Cover Total			**$94.40**
Tripod Assembly: (Taylor Eng)			
CV Joint (7oz)	4	$40.00	$160.00
Housing (31oz)	4	$249.00	$996.00
Cover & Dust Seal	4	$35.83	$143.32
3/8"dia. 24-1.75"lg Socket head cap screws (50pcs)*	1 box	$30.79	$30.79
Tripod Assembly Total			**$1,330.11**
Torsen Differential (T-1)	1	$375.00	$375.00
Torsen Differential Total			**$375.00**
Brake Rotor Assembly			
Caliper	1	$70.22	$70.22
Rotor	1	$134.40	$134.40
Brake Rotor Assembly Total			**$204.62**
Axles (Taylor Race Eng.)			
Gun Drilled Axle 4340 Rc50 14"max 10"min	2	$175.00	$350.00
Axles Total			**$350.00**
Drivetrain Material TOTAL			**$2,755.01**
Drivetrain Production TOTAL			**$2,585.00**
Misc. Expenses			**$534.20**
GRAND TOTAL			**$5,874.21**

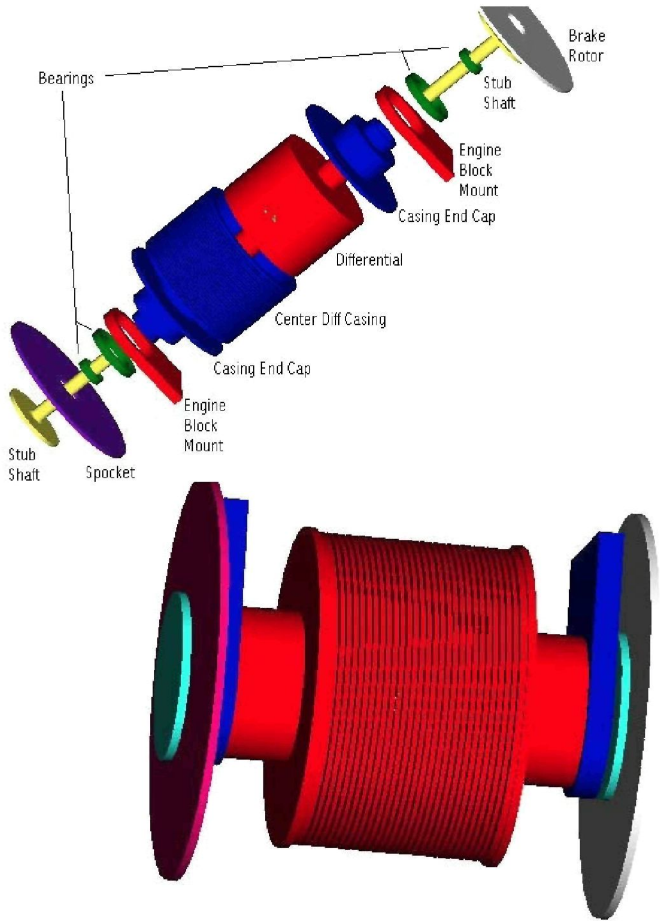
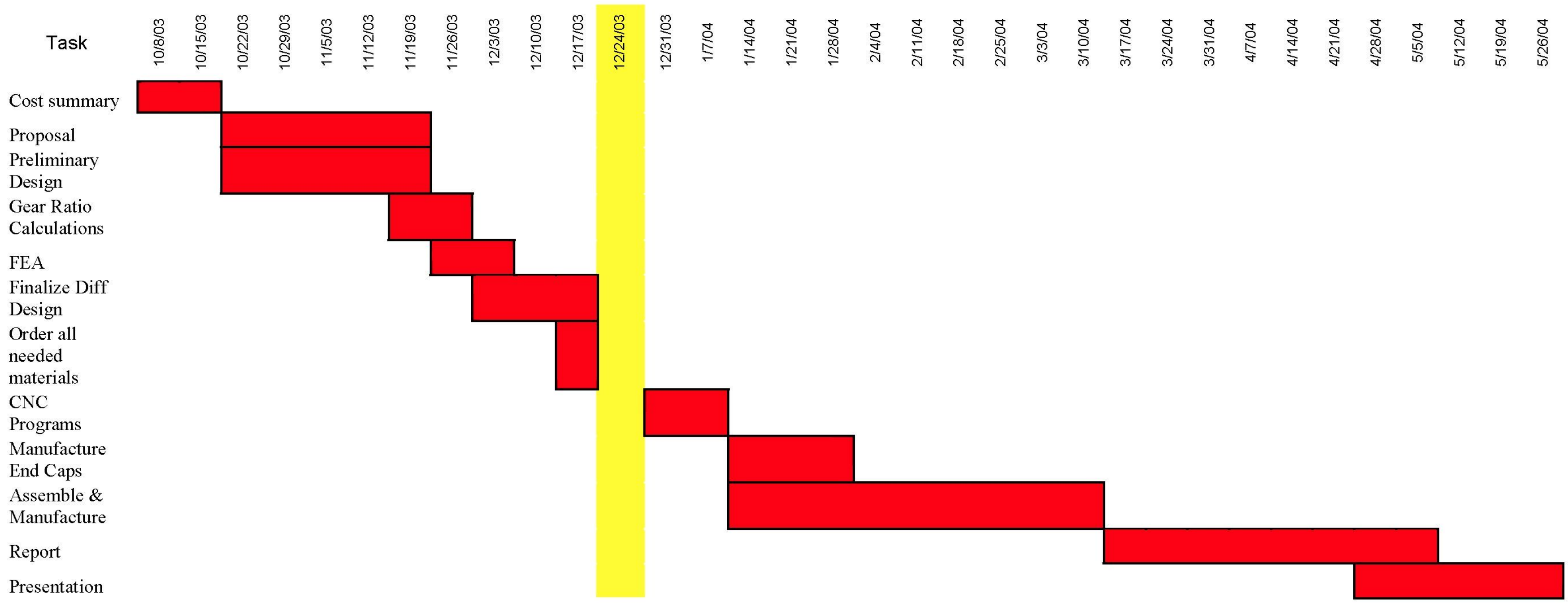


Figure 1 – Shown is a simplified version of our conceptual design (Excluding bulkhead)

Appendix A-3 - Project Gantt Chart.



Abstract

Each year the Society of Automotive Engineers (SAE) holds a competition in Pontiac, Michigan called Formula SAE (FSAE). Each year SAE releases a revised rulebook outlining the constraints of the upcoming year's competition. The racecar to be designed is an open-wheeled, mid-engine, rear-wheel drive racecar. This year's Drexel FSAE team has approached us with a project to design a completely symmetrical differential assembly using a Torsen differential. This differential will be mounted to the rear of the engine, placing no stress on the rear chassis of the racecar. This will design will allow a shorter wheelbase and narrower track, as well as bringing the center of gravity of the racecar closer to its centerline. We intent to manufacture a prototype differential assembly and rear chassis for testing and use on the 2005 Drexel Formula SAE racecar.