Design and Manufacture of a Rear Driveline Package including Limited Slip Differential for Formula SAE Applications

by

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ABSTRACT

This document describes the design and manufacture of a lightweight rear driveline package for a Formula SAE race car. The design focuses on all components needed to transfer power from the chain driven Honda CBR600 F4i to the rear drive wheels, and includes a custom limited slip differential housing, drive shafts, hubs, and wheels. The design is centered on a custom aluminum housing for Torsen® T1 gears, which provides limited slip and torque biasing between the two drive wheels. This type of differential has proven itself in the world of motorsports, especially in the Formula SAE series. This document demonstrates the design concepts and justifications, as well as the manufacturing processes needed to fabricate the designs. This work on the driveline package was developed with the hopes that it will be used in future years as a stepping stone for improved designs. Design choices and justifications have been explained, and manufacturing processes have been thoroughly described through the use of both text and figures to aid in the manufacture of future components.

Thesis Supervisor: Daniel D. Frey
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1.0 Introduction

The driveline package described in the following pages was designed and manufactured specifically for MIT Motorsports, for the Formula SAE® competition. The design focuses on all components needed to transfer power from the engine to the rear drive wheels, and includes a custom limited slip differential housing, drive shafts, hubs, and wheels. This document demonstrates the design concepts and justifications, as well as the manufacturing processes needed to fabricate the designs.

The project described here has been a substantial one, performed by a single student over the course of two academic terms. Undertaking a project such as this one is a significant time commitment, requiring countless hours of mechanical design, analysis, and machine time.

1.1 Formula SAE®

Formula SAE® is a collegiate design competition where students design, fabricate, and compete with an open wheeled formula style race car under the premise that a prototype vehicle is being developed for evaluation as a production item. With limited restrictions on the vehicle, teams are challenged to show their design, engineering, and fabrication prowess. Each year more than 120 collegiate teams from around the globe come together and pit their cars against each other in both static and dynamic events.

The static events are broken down into three categories: design, cost, and marketing. In the design event, experienced judges from industry with varying backgrounds scrutinize the vehicle, asking student engineers the reasons and justifications behind their design choices. Teams also give a design presentation, outlining their vehicles design features. Following the presentation and judging, a select few teams are selected for design semifinals where vehicles are scrutinized under a more careful eye and more time is allotted for an additional presentation. At the conclusion of the design event, points are awarded based on overall designs and how well teams could justify design choices.

The cost event consists of three different sections. Teams are judged on overall cost of the vehicle, a presentation of a cost report outlining all material and labor costs, as well as a manufacturing presentation. The overall goal of the cost event is to focus on minimizing cost throughout the entire design and manufacturing process, as material stock, machine time, labor, and retail parts are all factored into vehicle cost.

In the marketing event, two students from each team present to a panel of 'manufacturing firm executives' in an attempt to convince them that the design best meets the demands of the amateur weekend autocross racing market. Additionally, the car must be able to be profitably manufactured and marketed.

Teams attending the Formula SAE competition also earn points by competing in four dynamic events. These events are designed to test the performance and handling of the vehicles, and account for a majority of all points possible. The first of these events is the skidpad, which is designed to test the car's cornering capabilities. In this event, cars make two laps around a figure eight track, with the fastest time being recorded. Faster lap times correlate to higher lateral accelerations that can be sustained by the vehicle.

The second dynamic event is an acceleration event, designed to evaluate the vehicles straight line acceleration. Cars attempt to traverse a 75m straight course in as little time as possible. The performance of Formula SAE vehicles typically leads to 0-60 times of around 4 seconds.

The third dynamic event is an autocross event, where vehicles maneuver a tight course marked with cones. This event is designed to test the vehicles maneuverability and handling, combining acceleration, cornering, and braking into a single event. This event is not only a test of vehicle performance, but also of driver skill as points are awarded on how quickly the vehicle can complete a single lap.

The final dynamic event is an endurance event, designed to test the durability and robustness of the vehicle. In this event, teams must navigate a 22km road course with a driver change at the 11km mark. At this driver change, vehicles are scrutinized to ensure that all components are still in operating condition, and those that are not are removed from the event. Even the smallest of fluid leaks can lead to a car being disqualified from this event. Teams that finish all 22km are awarded points based on their overall time and its ratio to the fastest time recorded. Due to the high level of scrutiny at the driver change, it is not uncommon for less than one third of all vehicles to finish endurance. Endurance is worth the most points of all events, and is a large determining factor in a team's overall performance at competition.

Detailed information about the Formula SAE competition, rules, and scoring can be found in the official rule book[1].

1.2 MIT Motorsports

The driveline package described in this document was designed and manufactured for MIT Motorsports, the MIT Formula SAE team, for their MY08 vehicle. This vehicle is the 6th car designed and built at MIT and is thought to be the best vehicle to date. This vehicle was designed to compete in two competitions in 2008, Formula SAE® VIR held April 23rd-26th, and Formula SAE® held May 14th-18th.

This work on the driveline package was developed with the hopes that it will be used in future years as a stepping stone for improved designs. The entire design and manufacturing process has been well documented, and will be kept in the possession of MIT Motorsports for reference in future years. This document is to serve as the main reference to the designs and manufacturing processes undertaken; however, additional materials have been created and will be kept in the possession of the team. A design notebook was thoroughly used over the course of the design and manufacturing process and contains sketches, calculations, part drawings and other useful pieces of information. All of the CAD files have been sorted and named for easy reference in future years. Additionally, a plethora of pictures have been taken throughout the entire manufacturing process, highlighting machine setups, tooling, and operations.

One of the goals of this document is to outline the entire process used to create the vehicle driveline package such that one can get an idea of what to expect when tackling such a project. This will help future team members understand how things were done, what design decisions were made and the justifications behind them, and what manufacturing processes were used, in order to allow them to decide what to do and what not to do.

1.0 Design Philosophy

Before undertaking any design project, it is first necessary to consider all requirements and limitations that are present. These requirements and limitations are outlined in the following sections, and are integral to the design process.

Formula SAE emphasizes quick development of complicated designs, as teams usually spend on the order of six to eight months designing, manufacturing, and testing their vehicles. This places some important restraints on teams, especially those where teams are solely extracurricular and motivating team members to stay on task is difficult.

The key to having a successful team is successful transfer of knowledge between team members, such that they have the foundation necessary to iterate and improve upon designs from years past. Therefore, the design that is presented here and in the supporting CAD files are highly detailed. In the fast paced world of FSAE where the norm is occasionally "build it first, document it later," this level of detail is included since the driveline contains components have many intricacies and details that can easily be overlooked, leading to wasted time, and in the worst case, component failure.

All parts were designed using SolidWorks 2007 for CAD, and COSMOSWorks was the FEA package used to verify component strength for expected design loads. MIT Motorsports uses these software packages exclusively, as does the MIT Mechanical Engineering Department. This allows for easy CAD integration with other parts and components.

2.1 Functional Requirements

The driveline design presented here is an iteration on the driveline packages utilized in previous MIT Formula SAE vehicles. Keeping the driveline design of these vehicles in mind, as well as keeping additional restrains specific to MY08 in mind, a list of functional requirements was created for the 2008 driveline design.

- The driveline should be durable, requiring as little maintenance as possible
- Differential housing should be completely sealed and free of leaks
    - Fluid leaks in the endurance event are devastating, and should be avoided at all costs
- Half-shafts should be close to the same length
    - This will prevent torque steer, as well as help to minimize part count
- A suitable method of chain tensioning should be utilized, realizing that half-links do not exist in motorcycle chain

- The entire assembly should be lighter than in previous years without sacrificing component strength and durability

2.2 Manufacturing Requirements

A design is useless if it cannot conceivable be manufactured, regardless of how good of a design it may be. The manufacture of the entire driveline package is intended to be done in-house by MIT students, not professional machinists. This leads to a specific set of manufacturing requirements to be considered in the design process.

- Design of the differential housing should be based on an existing limited slip gear system
- The driveline must be designed keeping MIT Motorsports access to manufacturing facilities and tooling in mind
- All tooling and facilities needed must be those which can be operated by a student, not necessarily an expert machinist
- Material, tooling, and fabrication costs should be minimized

2.3 Integration Requirements

The driveline is not a stand-alone system, and must interface with other vehicle components. It is therefore necessary to fulfill certain integration requirements when designing the system.

- Driveline package should be designed to interface with a Honda CBR 600 F4i Engine, a chain-driven 600cc 4 cylinder engine used by MIT Motorsports
- Driveline components must be compatible with, and designed with suspension components and requirements in mind
- Differential should mount off the engine for modularity
- Differential must be placed such that power is transferred to the wheels regardless of what position the suspension is in
    - Driveshaft angles should always remain in the operable range
- The rear driveline components should share as many components as possible with the front suspension system, reducing part count

2.4 MIT FSAE Restraints

In addition to the requirements and restrains listed above, designing a component specifically for MIT Motorsports creates its own set of restraints.

- Operation, assembly, and maintenance must keep limitations of team facilities and members in mind
- Cost should be minimized
    - MIT Motorsports operates on a limited budget
- Lifetime considerations

- Formula SAE vehicles in general are subjected to harsh conditions of testing and at competition
- MIT Motorsports hopes to maintain a few vehicles such that multiple vehicles will be in running condition at a time. Therefore, components should be designed with sporadic use and testing in future years in mind.

3.0 Mechanical Design

The following sections describe the designs for the components that comprise the driveline package on the MY08 vehicle. Designs are shown, justifications are presented, and FEA loads and results are summarized.

3.1 Wheel Centers

Figure 1: MY08 Wheel Center Concept

Prior to MY06, off the shelf 4x100 hubs were used, alongside 13" BBS wheels. While this setup was easy to put together and generally looked good, the unsprung weight that it added to the car was extremely high. In MY06 a switch was made to custom hubs utilizing three steel drive pins to transmit torque to the wheels and three steel bolts to provide clamping. In conjunction with these custom hubs, custom wheel centers were designed to interface with the hubs. This new system saved nearly six pounds per corner.

The MY08 wheel center is an iteration on the MY06 design, utilizing the accessibility to improved manufacturing processes and improved FEA experience and knowledge, leading to reduced weight and manufacturing time. The wheel centers, made of 6061-T6, feature CNC located holes to interface with the drive pins and wheel studs on the hubs, as well as the wheel outer mounting holes.

3.1.1 Wheel Outers

The wheel offset chosen by the chassis group determined both the wheel outer selection, and influenced wheel center mounting. Keizer Aluminum Wheels' 13" three-piece small center design wheel outers were chosen for their lighter weight in comparison to the BBS wheels used in the past and other market options, as well as their lower price in comparison to other market options. By selecting a 2" outer shell, 4" inner shell, and mounting the wheel center from the outboard side, the 6" wide wheel and 1" offset desired by the chassis group were easily attainable.

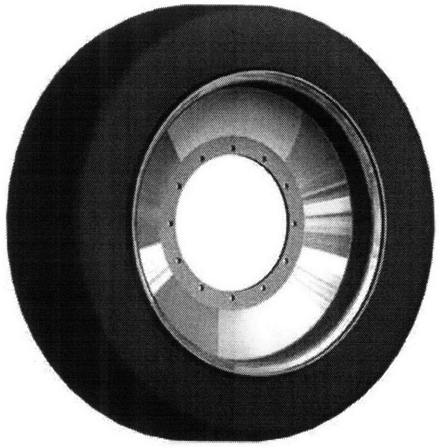

Figure 2: CAD Model of Keizer Wheel Shells and Goodyear Slicks

The wheel centers were designed such that they would interface with the 12 mounting holes on the wheel outers, as well as the hubs. Additionally, it was necessary to ensure that the wheel centers provided enough clearance for the brake calipers. In order to accomplish these goals, it was determined that 0.75" thick plate would be needed.

3.1.2 Material Selection

Aluminum was the obvious choice for the wheel centers, based on its machinability, strength, and weight. The choice of aluminum alloy was a more difficult decision, as the strength and cost are among the major differences in the different aluminum alloys. 2024 and 7075 are alloys that have a higher strength than most other aluminum alloys, yet still maintain good machinability, and 6061 is a good general purpose alloy having decent strength and machinability.

It is desirable to have enough wheels to create two sets of tires (one set of slick, and one set of rain tires) as well as have two spare wheels. While the use of 7075 or 2024 would allow for lighter components, procuring a plate of aluminum in the quantity needed to make ten wheel centers would be prohibitively expensive. While all aluminum alloys are cost the same on the FSAE Cost Report, MIT Motorsports operates on a fixed budget, and reducing costs is a key goal. Therefore, 6061-T6 plate was chosen.

3.1.3 Manufacturing Considerations

The wheel centers are relatively straightforward to manufacture, as will be seen in Section 4. The aluminum alloy chosen has good machinability, so the machining facilities available to students are more than capable of working with 6061.

The team has had much success with waterjetting components in previous years, and more specifically with waterjetting wheel centers. The wheel centers were designed such that the spoke pattern could be cut on a waterjet without too much difficulty. Access to a CNC Lathe in the Edgerton Student Shop also allowed for a curved surface to be used on the inboard side of the wheel center, reducing stress concentrations as well as weight from previous years. The mouting holes and drive pin holes are also designed such that they are easily located and drilled using a CNC Mill.

3.1.4 Estimation of Forces

The wheel centers, or more generally the vehicle wheels, experience loading from three different scenarios. To aid in the calculation of forces for each of these three scenarios, a spreadsheet created in 2005 by MIT Motorsports members to calculate spindle loads was modified to calculate the loads on the wheels.

The first of these loading conditions is forward acceleration or deceleration of the vehicle. Since the vehicle has much more stopping power than acceleration, the force on the wheels due to maximum braking effort were used. Using the spreadsheet, a load of 915 ft-lbs was calculated.

The second of these loads is that which occurs from lateral acceleration of the vehicle, occurring in turns. In addition to the projected vehicle weight of 410 pounds, a maximum theoretical acceleration of 1.5g was used in the calculations. This yielded a lateral load of 266 lbs, applied at the contact patch.

The last of the three loads seen by the wheels is due to bump, or essentially the effect of the car hitting a pothole or bump in the road. The maximum vertical acceleration due to bump was calculated by the suspension group to be 1.8g. This yielded a bump load of 2604 lbs.

3.1.5 Finite Element Analysis

The worst case loading scenario involves all three loading conditions occurring simultaneously, which is possible if hitting a bump in a corner under braking. Therefore, all three loads were applied to the wheel center simultaneously for FEA purposes.

Before applying the loads, the proper restraints were defined. The twelve mounting holes were fixed, and the area of the wheel center which contacts the hub was also defined as fixed. The lateral load was applied to the outer perimeter of the wheel center which contacts the wheel outers through a remote load, with the load specified at the contact patch. The bump load and the braking torque were both applied through the three drive pin mounting holes.

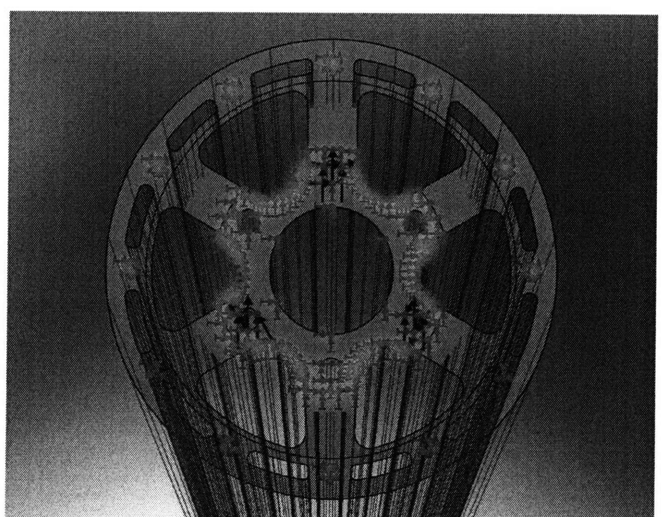

Figure 3: Wheel Center FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 1.4 for the 6061-T6 wheel centers. Although cyclical loading occurs on these parts, and aluminum is susceptible to fatigue, fatigue analysis was not performed. This would be a highly useful, and is recommended for future work.

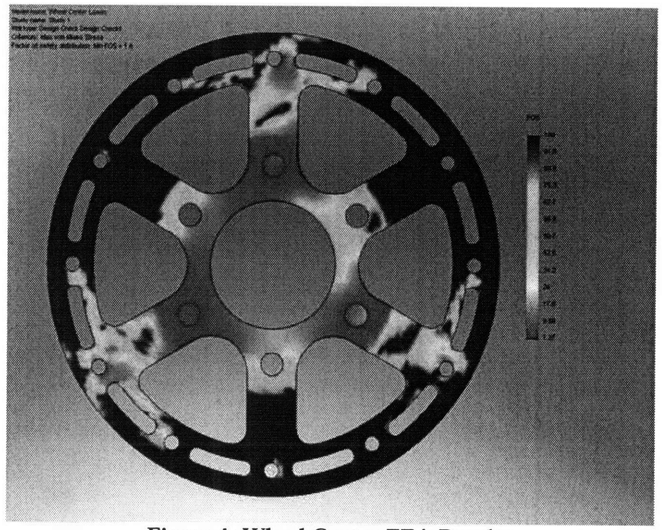

Figure 4: Wheel Center FEA Results

3.2 Rear Hubs

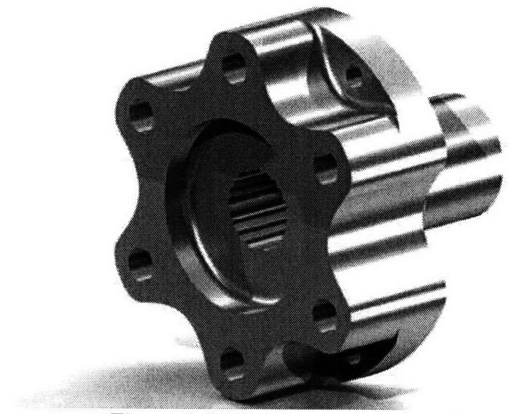

Figure 5: MY08 Rear Hub Concept

In order to bring power through the drive shafts and into the wheels, it was necessary to design custom rear hubs to interface with the custom three-pin three-bolt wheel centers. The rear hubs were splined to mate with the half-shafts to accept torque from the differential. The MY08 rear hubs are radically different from those which first employed the three-pin three-bolt system on MY06, featuring an outer contour to remove excess weight. The advances in weight reduction can be attributed to increased proficiency and detail in finite element analysis.

3.2.1 Integration with Rear Package

The rear hubs were designed such that they would interface properly with not only the wheel centers, but also the rear uprights, brake rotors, and half-shafts. The hubs were designed to press into bearings in the rear uprights, thus needed to be positioned such that the proper track width and wheel offset were achieved, in addition to ensuring that enough clearance was allotted to the brake rotor and caliper. For the drive pins, three 0.375" x 1.5" steel dowel pins were pressed into the hub, utilizing a press fit of 0.001". When pressed, the drive pins protrude from the hub surface 0.5" to transfer the torque to the wheel centers.

The brake rotors mount to the hub utilizing three AN4 bolts. As in previous years, the rotor mounts from the inboard side of the hub. A major change from previous years, however, is the ability to install and remove the brake rotors from the outboard side. This allows the brake rotors to be changed, should they need to be replaced for any reason, without the need to un-press the bearing from either the hub or the upright. Bearings are susceptible to damage when attempting to un-press them, so the elimination of the need to do so is an important design feature.

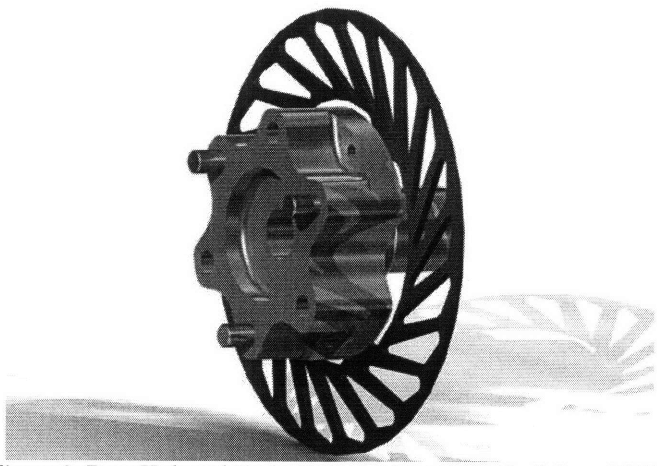

Figure 6: Rear Hub and Brake Rotors, Mounted to the Inboard Side

3.2.2 Material Selection

The rear hubs were made of 7075-T651 aluminum. This alloy is a very strong aluminum alloy and is also not as vulnerable to cyclical loading as other strong aluminum alloys. Although more expensive than 6061, the strength properties of 7075 far outweigh the cost, especially when there is only a need for four hubs.

Although the rear hubs have an outer diameter of 4", 4" round stock of 7075 was not available, so 5" stock was procured. Although this led to more material being removed while turning, removing more material is a better option than not having material at all.

3.2.3 Bearing Selection

The bearings used in the rear hubs were chosen by the chassis group and are standard Volkswagen wheel bearings. These bearings have been used on the previous three vehicles, and the team had excellent results with them. The bearings were installed in the rear uprights, as well as the front uprights of MY08.

3.2.4 Manufacturing Considerations

When manufacturing the hubs, the two most important tasks were ensuring that the drive pins were in the proper location and concentric with the bearing surface, as well as ensuring that the bearing surface was concentric with the inner hub bore. When cutting the holes for the drive pins, it was important to ensure concentricity between the mill and the hub bearing surface, which is easily accomplished to within 0.0005" using a dial indicator mounted in the spindle. Since the inner bore of the hub would be sent out to have splines cut by a third party, it was necessary to adhere to the tolerances they requested. Using a reamer, two hubs were provided to Rockford Acromatic Products that were within their specified tolerance.

3.2.5 Estimation of Forces

Similar to the wheel centers, the hubs experience loading from three different loading scenarios. The loads from these three scenarios were calculated in a similar fashion to those calculated for the wheel centers, using the spindle load spreadsheet.

For the load due to braking effort, a torque of 915 ft-lbs was calculated. For the lateral acceleration of the vehicle, a lateral load of 266 lbs was used, applied at the contact patch. The bump load was calculated to be 2604 lbs.

3.2.6 Finite Element Analysis

Similar to the wheel center analysis, the worst case loading scenario on the rear hubs also involves all three loading conditions occurring simultaneously. All three loads were applied simultaneously to the rear hub.

For the FEA, the rear hub was restrained at the inner bore, which would normally contact the spline of the half-shaft. The lateral load was applied to the outboard face of the hub through a remote load specified at the contact patch. The bump load was applied through the drive pin holes, and the braking torque was applied through the three brake rotor mounting holes.

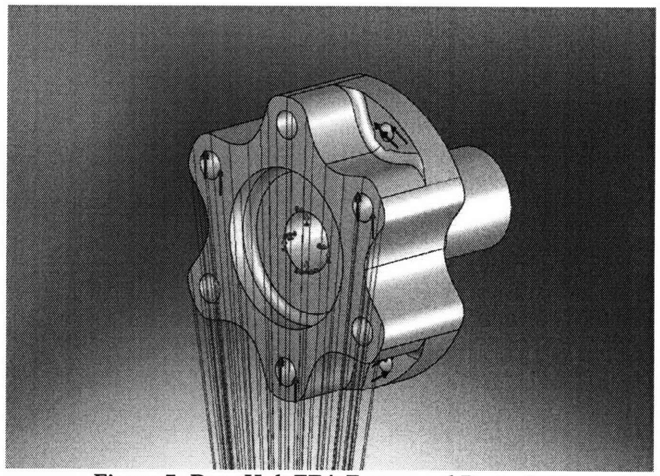

Figure 7: Rear Hub FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 1.8 for the 7056-T651 rear hubs, located at the outboard side of the inner bore.

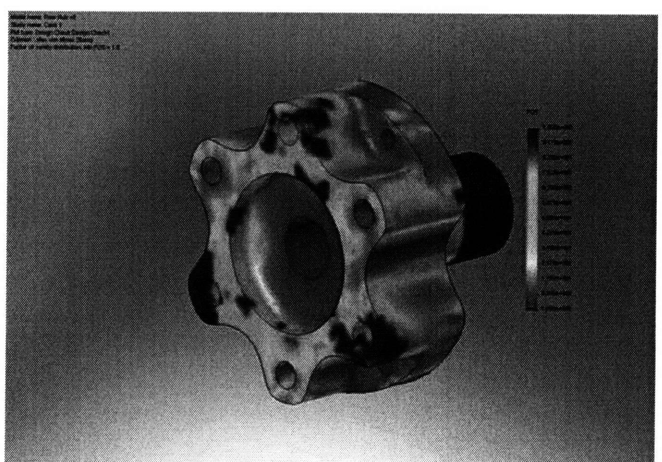

Figure 8: Rear Hub FEA Results

3.3 Limited Slip Differential

The design presented here includes all components that are required to adapt the gearing from a Torsen® University Special differential to a Formula SAE application. This includes everything from the actual custom aluminum differential gear housing, input bell and sprocket, to the two aluminum mounting brackets. Additionally, methods for chain tensioning, case sealing, and stub-shaft supporting and sealing are detailed.

The design presented here is an iteration of the previous differential designs utilized by MIT Motorsports. Every effort has been made to ensure that this design builds upon the knowledge and information obtained from previous designs, hopefully making this design as reliable and high performance as previous designs.

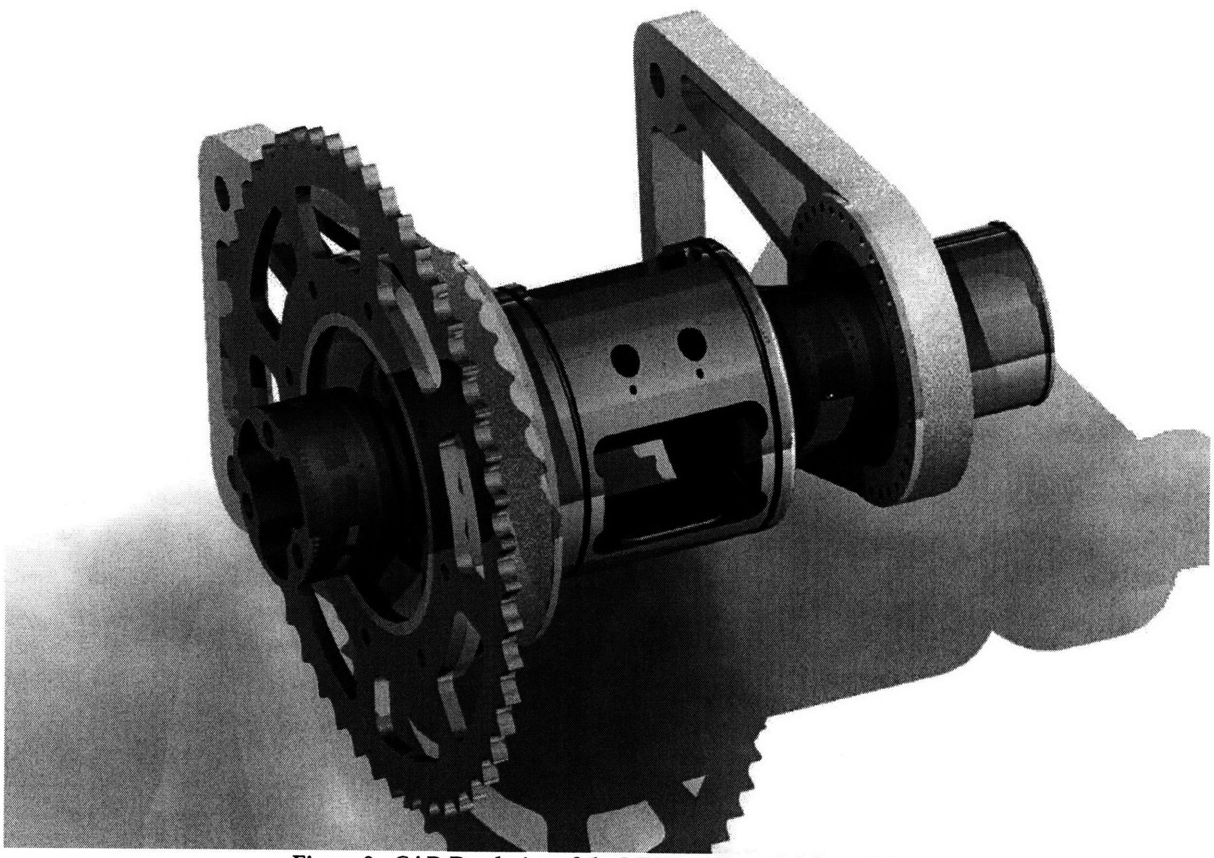

Figure 9: CAD Rendering of the MY08 Differential Assembly, showing all components except differential gearing and sealing sleeve

3.3.1 Differential Mounting Brackets

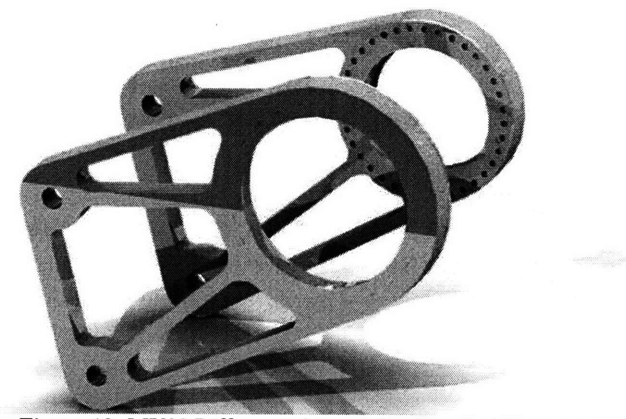

Figure 10: MY08 Differential Mounting Bracket Concept

The differential brackets mount off the CBR 600 F4i engine swing arm mounting points. The swing arm mounts are approximately 6" apart, which allows for just enough room for the differential internals between the brackets. This mounting method has been employed for a few years on MIT Motorsports vehicles, and has demonstrated that this is a suitable mounting method. The chain tension forces on the stock bike are transmitted through these points, so it is known that these points are more than capable of supporting the loads that will be applied through our vehicles driveline.

A direct load path to the engine provides many benefits. With the entire vehicle designed off of the engine, mounting to the engine allows us to take advantage of its high strength while minimizing the addition of structural components on the frame. Also, the engine is known to be much stronger than the thin walled structural tubing used for the vehicle frame. If the differential is mounted only to the frame, the high loads transmitted through the driveline could distort these thin-walled members, causing the differential to bind or causing other misalignments that could lead to damage. Additionally, high tolerances can be held when machining aluminum brackets that are not possible if utilizing a welded sheet metal mounting scheme.

3.3.1.1 Major Differences from Previous Design Iterations

MY07 was the first year that completely open differential brackets were used, a drastic change from previous iterations where the brackets had one closed side of at least 1/8". This design change greatly improved overall vehicle packaging, as cooling lines were able to be run through the brackets. The MY08 brackets are of similar open design, and it is expected that cooling lines will once again be run through them.

Substantial changes in rear suspension geometry were employed on MY08, lowering the front lower suspension point by 1". This change led to differences in rear box geometry from MY07, essentially changing the lower mounting point of the differential brackets. This led to a larger distance between the top and the bottom mounting points, leading to differential brackets which were wider at their front ends. This had a limited effect on the loading of the brackets, but required the brackets to be larger, and thus heavier, than the brackets on MY07.

3.3.1.2 Material Selection

The differential brackets are made of high strength 7075-T651. This allows for large amounts of material to be removed, while still maintaining high structural integrity. The good fatigue properties of 7075 are also important, since the differential brackets see lots of cyclical loading. With the bearings being 16mm in width, a good choice of bracket width is 0.75". This allows for enough material to support the bearing, as well as additional space for a lip to be employed on the outboard sides of the brackets to retain the bearings.

3.3.1.3 Bearing Selection

By mounting the differential off of the engine swing-arm mounts, the sprocket must be mounted outside of the differential brackets. This also requires that a large bearing be used on the sprocket side such that torque can be transmitted through it. With the opposite side of the differential housing seeing a much smaller load, a smaller bearing can be used.

Single row deep groove ball bearings, with double-lip contact seals were chosen from NTN. For the sprocket side, a 6916LLU bearing was chosen, which has a bore of 80mm, an OD of 110mm, and a width of 16mm. For the opposite side, a 6010LLU bearing was chosen, which has a bore of 50mm, an OD of 80mm, and a width of 16mm. The seals are important to keep dirt and grime out, prolonging the life of the bearing.

3.3.1.4 Chain Tensioning

Chain tensioning is accomplished through two different methods. The first method utilizes eccentric bearing mounts on each differential bracket. The bearings are pressed into the 'eccentrics', and a lip on the outboard side of the eccentric retains the bearing. When the eccentrics are rotated inside the differential bracket, they can shift the entire differential housing assembly toward or away from the engine, decreasing or increasing chain tension respectively. Both the left and right eccentrics feature 36 different mounting holes, allowing for fine adjustment of chain tension. Once the eccentrics are rotated such that sufficient chain tension is obtained, they are each securing in place by using 3 10-24 bolts, attaching them to the differential brackets.

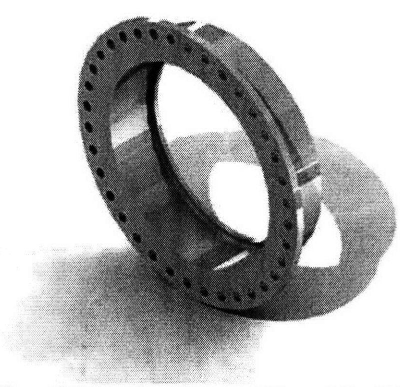

Figure 11: Differential Bracket 'Eccentric' used for Chain Tensioning

Should this method of tensioning not be sufficient, ovular parts with off-center holes could be inserted into ovular holes at the mounting points of the differential brackets. Depending on which way these 'footballs' are inserted into the differential brackets, the differential assembly can be moved forward or backward, essentially adding or decreasing chain tension.

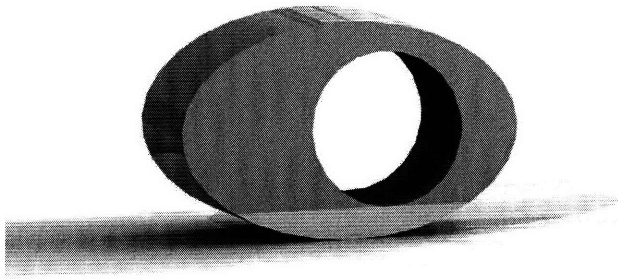

Figure 12: 'Football' used for Chain Tensioning

3.3.1.5 Manufacturing Considerations

Since 7075 plate is expensive, especially a piece 0.75" thick, every effort was made to minimize material use. The brackets were designed such that they would both be able to be cut from a single 12" x 12" plate. With the brackets both fitting on a single plate, they were easily cut on a Waterjet, decreasing manufacturing time from previous years which cut the differential brackets using a ½" endmill.

3.3.1.6 Estimation of Forces

A detailed analysis and calculation of forces seen by the differential brackets was performed by both Keith Durand and Tony Scelfo in their undergraduate theses.[2,3] The details are not repeated here, and their theses should be consulted for analysis. The loads applied to the brackets were to mimic the maximum chain tension of 2,200 lbs.

3.3.1.7 Finite Element Analysis

Restraining the differential brackets at the mounting points, the load was applied to the bearing face of the brackets. The analysis is similar for both the left and right brackets, with the only difference being the right bracket seeing a smaller load since there is a significantly longer lever arm between the sprocket and the right bracket bearing.

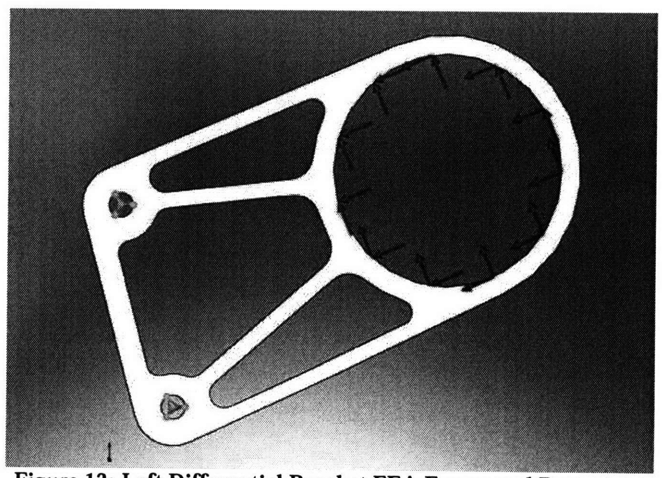

Figure 13: Left Differential Bracket FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 1.2 for the 7056-T651 left differential bracket, and 1.3 for the 7075-T651 right differential bracket. These safety factors are very similar to those used on the MY07 brackets, which as mentioned previously are very similar in design to these. MY07 has had multiple hours of testing and competition, and the brackets, to date, have held up extremely well.

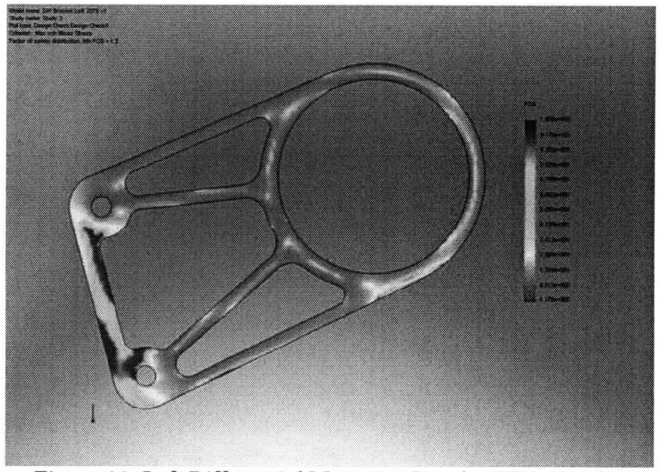

Figure 14: Left Differential Mounting Bracket FEA Results

3.3.2 Differential Center Section

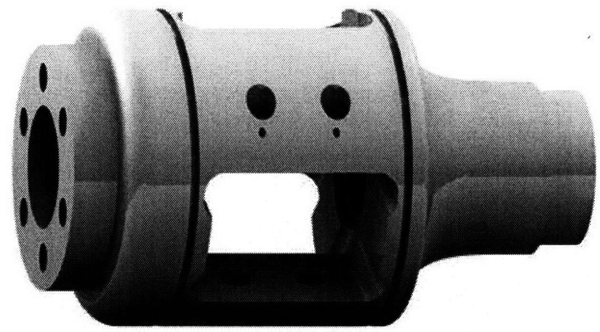

Figure 15: MY08 Differential Center Section Concept

3.3.2.1 Major Differences from Previous Design Iterations

The design of the differential center section presented here is an iteration of the MY06 vehicle differential. While the general concept is very similar to the MY06 design, there are still some major design changes. The two largest changes are the curved profiles on either end of the housing. In addition to reducing stress concentrations over the previously straight cuts, these splines allow for a greater reduction of material while maintaining sufficient housing strength. Additionally, a more detailed finite element analysis has been performed this year than in previous years. This means that lower safety factors can be used with confidence on the housing.

3.3.2.2 Material Selection

The differential housing is made from 7075-T651 aluminum. As mentioned in previous sections, 7075 is a very strong aluminum alloy and has good resistance to cyclical loading, to which the differential is greatly subjected to. The differential housing is 4" in diameter, but the nearest size of aluminum stock that could be obtained was a piece with a 5" diameter, as was the case with the rear hubs. Although not really a problem, time and money could have been saved by using a piece of stock with a smaller diameter.

The differential element gears see a tremendous amount of force, and the design of the gearing causes them to be pressed up against the face at either end of the journal pin under loading. With an aluminum housing, even one made of 7075, the repeated abuse of hardened steel riding on an aluminum face is less than desirable. In order to prevent wear on the housing, which could lead to the eventual failure of the piece, thrust washers were made to fit on each side of the element gears between the hears and the aluminum face. These washers were made of hardened steel, and were surface ground to 0.0625" at the MIT Central Machine Shop after being CNC Milled to the proper size and shape.

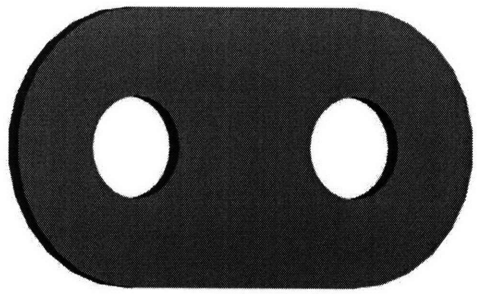

Figure 16: CAD Drawing of Steel Thrust Washer

3.3.2.3 Bearing and Seal Selection

3.3.2.3.1 Case Sealing

The differential center section must hold oil to lubricate the gears, preventing wear and failure. The differential must therefore have some sort of sealing mechanism to keep the oil in the housing, but at the same time ensure that no oil escapes the housing. With the Formula SAE competition penalizing heavily for fluid leaks (disqualification from Endurance), having no leaks is a top priority.

Sealing is done utilizing an aluminum sealing sleeve that fits over the differential center section. This sleeve is sealed using two Viton o-rings that are placed into grooves cut into the center section. Viton is the material of choice for racing applications such as this since it can withstand temperatures of up to 400° F, and does not react with gear oil. O-rings with a dash number of 240 (Nominal OD = 4", Nominal ID = 3.75") and a Durometer Shore of 75 were selected. The o-ring grooves in the center section were cut to be 20% wider and 80% as deep as the 0.139" diameter of the nominal 1/8" o-rings, allowing for proper o-ring compression when the seal is installed.

A large amount of force is required to press the sleeve over the o-rings creating a tight seal, especially with the clearance of only 0.005" between the center section and the sealing sleeve. Even with this large force, it is still necessary to keep the sealing sleeve from rotating on the o-rings, possibly causing damage. In order to prevent rotation between the center section and the sleeve, a ¼" steel dowel pin is pressed into the center section and mates with a slot cut in the sealing sleeve. Additionally, a 10-24 x ½" bolt is used to keep the sleeve from moving side to side.

The sleeve is drilled and tapped to accept a 1/8" NPT drain plug, used for filling and draining the gear oil from the case. The plug is located over a element gear window, and this is simple to do through the use of the retaining pin.

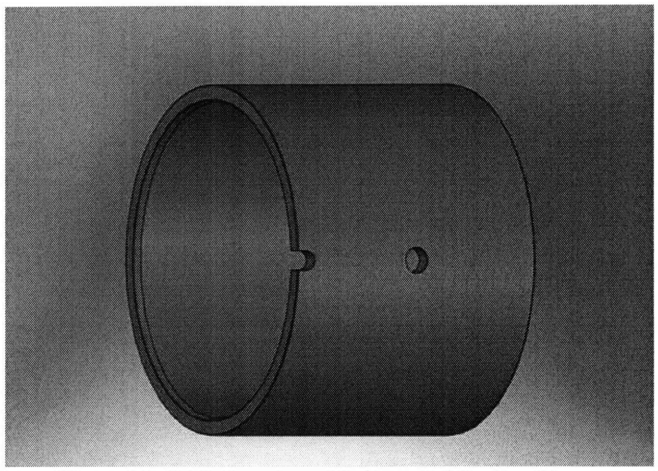

Figure 17: CAD Drawing of Differential Sealing Sleeve

3.3.2.3.2 Stub-Shaft Bearings & Seals

The design of the differential housing has the stub-shafts passing through seals and then bearings when inserted. Shaft seals from Chicago Rawhide featured a 40mm OD and a 30mm ID, and have sealed the 30mm stub-shafts well in the past.

The bearings used to support the two stub shafts were 20mm wide needle bearings, with an OD of 40mm and an ID of 30mm. With the bearings sharing a similar OD to the seals, the bearing pocket and the seal pocket can be made in one boring operation on the lathe. These bearings, which don't have an inner race, fit perfectly with the 30mm ground stub-shafts and provide adequate support. The open design of the bearings lends itself to a lubricated environment, as is seen with the seals placed on the outboard side of the bearings.

Figure 18: Inboard Stub-Shaft, Stub-Shaft Bearings, and Stub-Shaft Seals

3.3.2.4 Manufacturing Considerations

Manufacturing the differential center section was the hardest of among all driveline components, requiring multiple difficult setups and multiple operations. What also complicates the process is that very high tolerances need to be held in order to maintain proper differential function; the journal pins need to be in a precise location, the element gear windows must be a precise size, the inner bore must be an exact size for the side gear washers to ride on, and there are many other strict tolerances that must be held.

CNC Lathe work would be used to create the splines on the two ends of the housing, and CNC Mill work would be used to create the windows, journal pin holes, and other features. A rotary vice would be used such that a window could be cut, the part could be rotated, and the next pocket could then be cut.

3.3.2.5 Estimation of Forces

A detailed analysis and calculation of internal forces for the Torsen gearing were performed by Rich James in his undergraduate thesis in 2004. The details are not repeated here, and his thesis should be consulted for the analysis.[2]

Under acceleration, the maximum load that the side gears impart on their respective housing faces is17,164lbs. Also under maximum load, the element gears place 5,721lbs of force on the thrust washers.

3.3.2.6 Finite Element Analysis

Restraining the three drive-pin holes, the two loads were applied onto the differential housing. The two circular faces onto which the side gears act were loaded with a normal force of 17,164lbs. Under acceleration, the element gears will all press on the same thrust washer in their respective windows, so the 5,721lb normal force was applied to three of the six thrust washer faces.

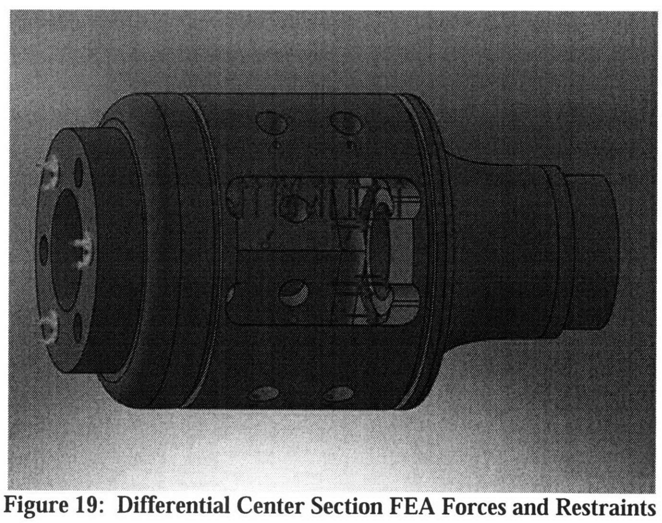

Figure 19: Differential Center Section FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 0.82 for the 7056-T651differential housing. However, this minimum FOS is only located at a small area on the outer diameter of the housing at one of the journal pin holes. The rest of the housing has a safety factor larger than two, there is confidence that the part will not fail, especially because this area is not critical to the structure of the part.

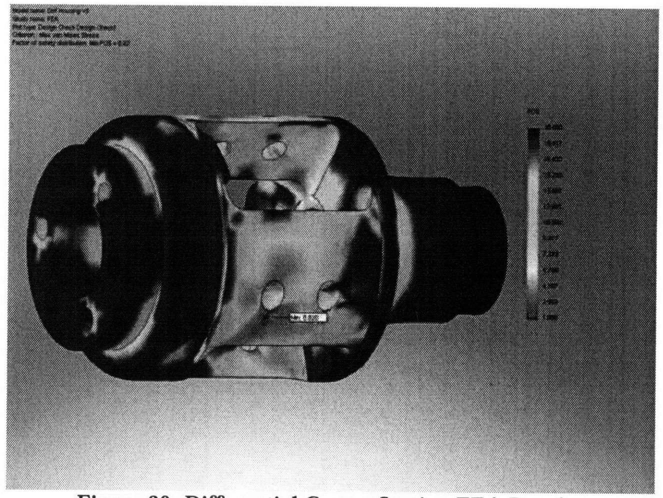

Figure 20: Differential Center Section FEA Results

3.3.3 Drive Components

3.3.3.2 Input Bell

The only way to transfer torque from the differential housing to the sprocket is through the use of an input bell which bolts onto the left side of the housing. The input bell is necessary because the torque must be transmitted through the bearing in the left differential bracket.

The torque is transmitted to the input bell using three 3/8" drive pins which are pressed into the differential housing. Clamping force is provided through three 5/16" AN bolts with drilled heads to allow for safety wiring. Helicoils are used in the body of the differential housing to provide a hard steel surface for the fine threads of the AN hardware.

While the input bell needs to transmit high loads, it does not necessarily have to be a hefty part. Made from 2024 for its strength and fatigue properties, the input bell interfaces well between the sprocket and the differential housing. These two components are connected using eight ¼" AN Bolts.

The torque applied was 1,200 ft-lbs. The maximum tractive capacity of the Goodyear slicks are 1,000 ft-lbs. This means that the tires will spin at any torque greater than 1,000 ft-lbs. Therefore, the maximum possible load that the sprocket would likely see is 1,000 ft-lbs. Adding 20% as a safety factor, the 1,200 fl-lb torque was derived.

With the part restrained at the six holes for the bolts and pins, the 1,200 ft-lb torque was split and applied over four of the eight sprocket mounting holes. Additionally, an axial clamping force of 10,000 lbs was applied to the face of the input bell where it contacts the differential housing.

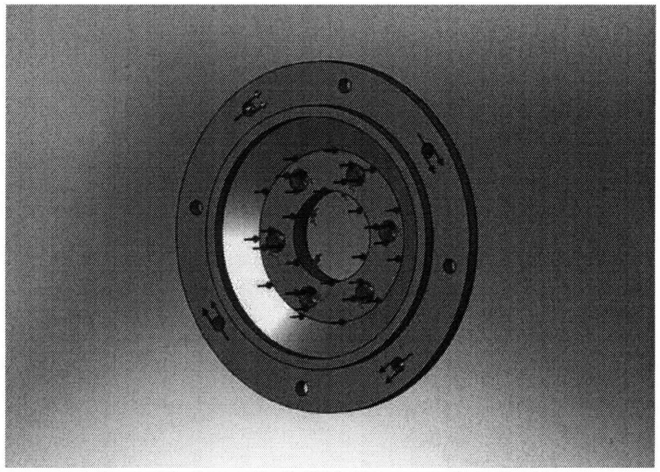

Figure 21: Input Bell FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 8.5 for the 2024input bell, demonstrating that the input bell can transfer large loads without being an excessively large piece.

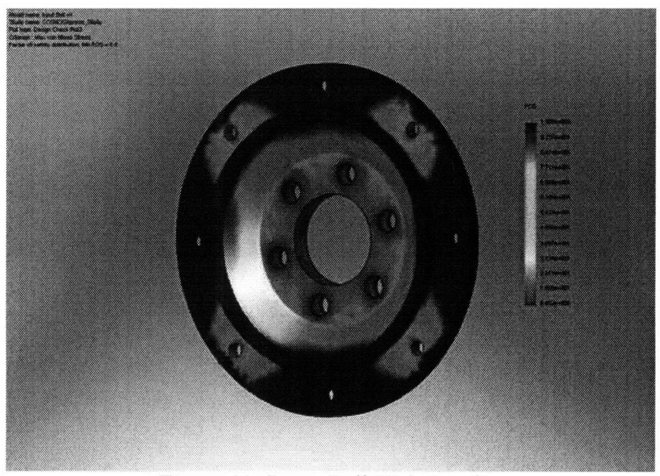

Figure 22: Input Bell FEA Results

3.3.3.2 Sprocket

The driven sprocket was purchased from Rebel Gears, and is made from 7075 Aluminum. In 2006, the switch was made to run a 12 tooth drive sprocket and a 48 tooth driven sprocket. This drive ratio has proven to be successful, and was selected again for MY08. The purchased sprocket is a 48 tooth 520 pitch sprocket blank, meaning that there is no design or spoke pattern. A blank was selected so that custom mounting holes and a pattern could be machined.

A simple eight-spoke pattern was chosen to accompany the eight ¼" mounting holes that would be used to connect the sprocket to the input bell. Finite element analysis was used to determine whether the spoke pattern would support the loads that would be applied to the sprocket.

Restraining the eight mounting holes, a torque was applied on half of the sprocket teeth, simulating the torque that would be applied by the chain. Similar to the input bell, the maximum torque seen is 1,000 ft-lbs. Adding 20% as a safety factor, a 1,200 ft-lb load was applied.

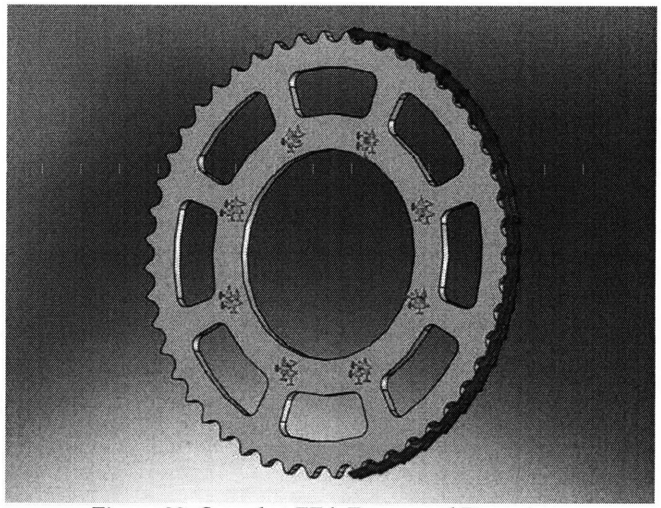

Figure 23: Sprocket FEA Forces and Restraints

This loading scenario yielded a minimum factor of safety of 1.0 for the 7075 sprocket.

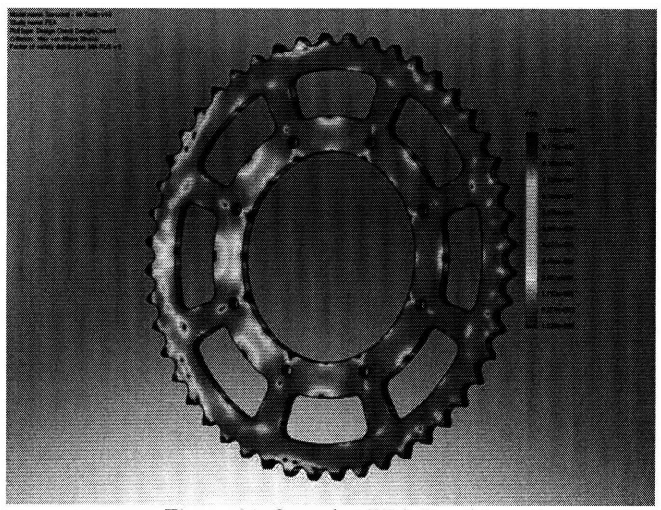

Figure 24: Sprocket FEA Results

3.3.3.3 Chain

The chain selection was based primarily upon the available sprockets. Unfortunately, a source for a 12 tooth driven sprocket with a tooth size of 428 was not found. The only 12 tooth sprocket that was found was 520 pitch, so the driven sprocket and the chain also had to be 520 pitch. Investigating other sources for a 428 pitch front sprocket for the CBR 600 F4i would allow weight to be saved not only on both sprockets, but also on the chain guard as well, which has a width defined in the rules of three times the chain width. Reducing the width of the chain would obviously then reduce the width of chain guard, and a thinner chain guard obviously weighs less.

The chain selected is a 520 pitch o-ring-less chain that is designed for racing applications. The two ends of the chain could be connected using either a master link, or through the use of a chain tool. A master link is generally preferred to the use of a chain tool, but either method is acceptable. In this application, the chain was spliced together using a chain tool.

3.4 CV Joints and Axles

The CV Joints and Axles used were part of a kit designed and marketed specifically toward Formula SAE vehicles. The kit, produced by Rockford Acromatic Products, has been used with great success in the past three MIT Motorsports vehicles, but was discontinued two years ago. Taylor Race Engineering recently began producing a similar kit, which they are also selling for a price comparable to the discontinued Rockford kit.

MIT Motorsports had a spare Rockford FSAE Kit, which was used for MY08 in order to avoid the cost of purchasing a new Taylor Race kit when another essentially free set was already available. The Taylor Race kit is essentially the same as the Rockford kit, but weighs slightly more and has a different inboard stub-shaft. This difference, although not major, will have to be accounted for in future years if the Taylor Race kit is used.

3.4.1 Outboard Stub-Shafts

The outboard stub-shafts are splined to accept a Polaris hub, and feature a threaded end. The rear hubs are splined to accept the stub-shaft spline, and a castle nut and cotter pin are used to restrain the two parts together. An aluminum spacer is also used fitted over the inboard end of the stub-shaft, and is designed such that when the castle nut is tightened, the spacer clamps the hub and the inner race of the bearing.

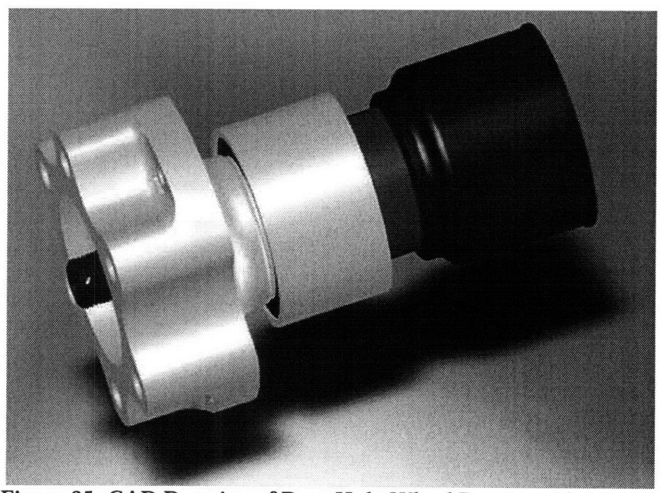

Figure 25: CAD Drawing of Rear Hub, Wheel Bearing, Aluminum Spacer (Shown in Green), and Stub-Shaft

3.4.2 Inboard Stub-Shafts

The inboard stub-shafts are splined to interface with the Torsen gearing. They also feature a 30mm OD section, which serves as a good bearing surface. The stock stub-shafts had a diameter of slightly more than 30mm, but when purchasing the set they were ground down to 30mm by Rockford. The splined ends have ring locks, and when pressed into the differential side gears serve as positive retention.

3.4.3 Axles and Tripods

The axles feature tripods on their ends, which is what allows them to rotate the two stub-shafts at a constant velocity. A 14" half-shaft is used on the left side, and a 15" half shaft is used on the right side. Rubber boots serve to seal the tripods in the stub-shafts.

4.0 Manufacturing

The following section describes the manufacturing processes needed to fabricate the designs that were presented in the previous section. Manufacturing processes have been thoroughly described through the use of both text and figures to aid in the manufacture of future components.

4.1 Wheel Centers

The manufacture of the wheel centers for the MY08 vehicle required three distinct steps performed on three different CNC machines. Each of these steps was optimized with speed of manufacturing in mind since a total of ten needed to be made (a set of slicks, a set of rains, and two spares). In addition to these manufacturing steps, a local metal finisher was used to anodize the centers for a more finished look.

Figure 26: Completed wheel, featuring custom wheel center, Keizer wheel outer, and Goodyear Eagle Tire

4.1.1 Waterjet Cutting

MIT Motorsports has realized the convenience and speed of manufacturing components using a waterjet, and the wheel centers seemed like the perfect place to utilize waterjet cutting. Waterjets can cut complex geometry in thin or thick materials relatively easily and quickly, and the wheel centers were no different.

Since the final width of the finished centers is 0.7", 0.75" plate was an obvious choice for stock. A large plate of 6061-T6 was purchased from Admiral Metals in Woburn, MA. A large plate was chosen, instead of smaller single wheel center-sized pieces to simplify the waterjetting process. Weighing much more than a single plate, it is much less likely for the large plate to shift during cutting, thus eliminating the chance of errors and wasted stock. Although a large plate proves to be more difficult to transport and maneuver, the advantages gained in the waterjetting process far outweigh the hassle of transporting it.

The wheel centers were cut on quality 3 on an OMAX waterjet in the Aero/Astro machine shop. With the thickness and large number of cutouts required, each wheel center took 25 minutes to complete. Although this may seem like a long time, using a waterjet instead of a CNC mill for this operation saved countless hours.

Although the tolerances kept with waterjetting are usually acceptable, none of the critical geometry was waterjet to ensure concentricity with the hubs and the Keizer wheel outers. Unfortunately only nine wheel centers were waterjet due to material and time constraints. This was not seen as a large issue however, as the team generally does not use rain tires, reducing the need for a spare rain tire.

Figure 27: Wheel Centers after Waterjetting

4.1.2 CNC Milling

After waterjetting the wheel centers, the mouting holes for the wheel outers, the wheel bolt holes, as well as the drive pin pockets were machined. Whenever machining more than a few of the same part, it proves to be useful to create a jig to aid in the machining process. Not only do jigs allow for properly orienting the part, but it allows the same zero to be used for machining each component, decreasing setup times.

A Bridgeport EZ-Trak was used for the CNC machining. The jig that was created for the wheel centers utilized two 3/8" steel pins to properly clock the wheel so the holes could be drilled in the proper orientation. The jig also was created such that the rear-left corner of the vise was set as the zero point for the CNC operation. By placing the wheel center to be machined in the jig, and then ensuring that the left edge of the center was in line with the left edge of the vise, the zero was set properly and quickly each and every time.

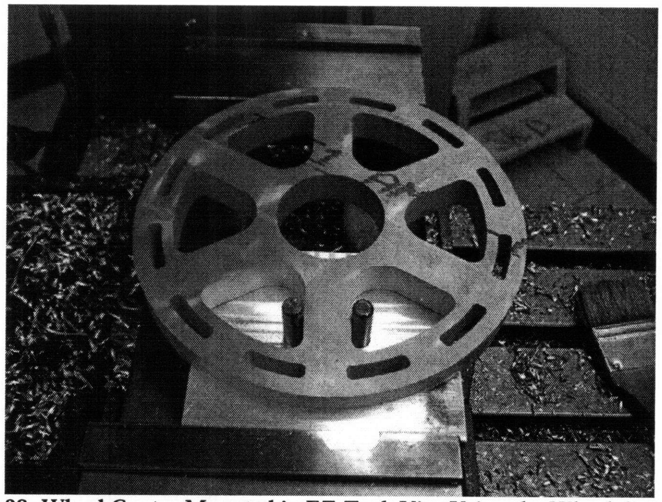

Figure 28: Wheel Center Mounted in EZ-Trak Vice Using the Wheel Center Jig

Once properly oriented on the mill, the twelve ¼" mounting holes for the wheel outers were drilled. First a center drill was used, followed by a ¼" drill. Due to the large number of holes, reaming was not necessary as the centers and the outers would be adequately constrained with the twelve AN4-10A bolts.

The three holes for the wheel bolts were then drilled, first using a center drill followed by a size W drill. Although AN-6 bolts are used to secure the wheels to the hubs, the holes in the centers were drilled oversize since the pins are designed to take the wheel torque, with the bolts only designed to clamp the wheel to the hubs.

Since the drive pins need to transfer the torque from the hubs to the wheels, the fit between the two should be very precise, with little or no slop. As was shown in previous years, if the location between the pins and the holes on the wheels are even the slightest off (thousands of an inch), they will not mate together. Thus it is imperative that steps are taken to ensure both holes are in the proper location and straight. In order to ensure the holes in the wheel centers were in the proper location, an undersized 3/8" endmill was used to drill the holes. Endmills are much stiffer than drills, so using an endmill to drill achieves higher tolerances. After drilling, the holes were reamed using a 0.378" reamer. This allows for ease of mounting and un-mounting wheels, while ensuring that the fit is still tight.

4.1.3 CNC Lathe Work

This final step in the machining process was to create the profile on a CNC lathe. The chuck on the HASS CNC Lathe in the Edgerton Student Shop is capable of holding the wheel centers from the center hole. Not only is this a convenient place to clamp the piece, but it also eliminates any possibility of running the tool into the chuck when cutting the profile. Since the part cannot be clamped from the outside edge which would provide the most secure hold, it was necessary to ensure that the part was tightly clamped, to ensure it was not thrown while turning.

A cutter with a carbide insert was used, and provided a good surface finish. As when turning any piece with discontinuities, such as the wheel centers, it is important to make sure proper speeds and feeds are used to ensure a good finish, while not having too much chatter.

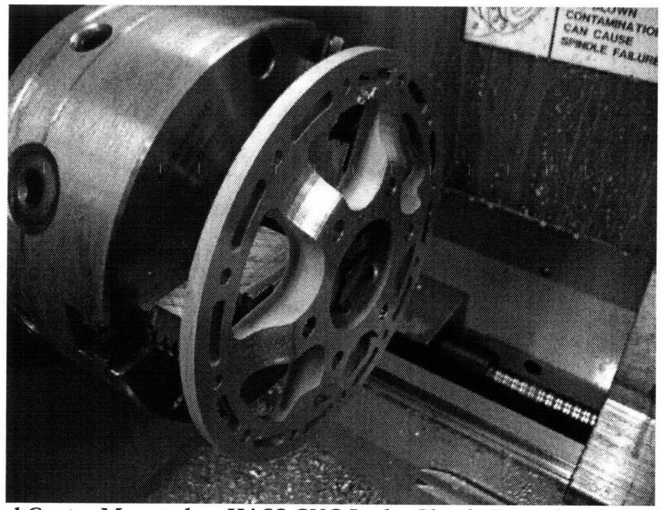

Figure 29: Wheel Center Mounted on HASS CNC Lathe Chuck, Immediately Following Turning

4.1.4 Metal Finishing

Although the main purpose of a racecar is to go fast, this does not mean that appearance should be sacrificed; the car can go fast and look good at the same time. Therefore, the decision was made to anodize the wheel centers to give them a more finished look. A local metal finisher, Federal Metal Finishing, was found and they were able to anodize the wheel centers in black for a very reasonable price of $75.

Since anodizing adds a very small layer of material onto the surface, it was necessary to re-ream the drive pin holes in the wheel centers. Once this was done, the fit was checked with the hubs, and when deemed acceptable, the wheel centers were able to be mounted onto the wheels.

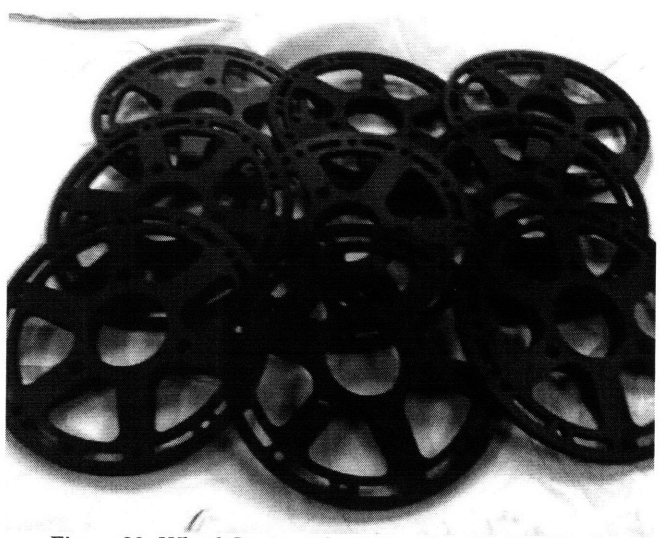

Figure 30: Wheel Centers after being Anodized in Black

4.2 Rear Hubs

The rear hubs were created using three machining processes. First, the profile was cut on a CNC lathe, followed by work on a manual lathe, and then holes and the contour were created on a

CNC mill. Since the hubs must transfer a torque between the half-shafts and wheels, they are splined to interface with the half-shafts. This part of the process was outsourced.

The front hubs, rear hubs, and differential housing are all made from 7075-T651 aluminum round stock, so a large section was purchased from Admiral Metals. This piece was cut into more manageable pieces using a horizontal bandsaw. This process is relatively straightforward, as the operator just has to ensure that enough coolant and wax are used on the blade.

4.2.1 CNC Lathe Work

The CNC lathe work was done in two operations, in order to machine both sides of the hub. In the first process, the hub blank which was cut to approximate length on the horizontal band saw was clamped in the chuck of the lathe, and made concentric using a dial indicator. Using a carbide cutter, the outboard side of the hub was turned down.

After this process was completed, the part was turned around and clamped on the newly created outboard side. The contour of the inboard side was then turned down. The bearing surface on the hubs was left oversize, as mixed experience has been encountered with the HASS CNC Lathe and critical dimensions. In order to avoid any wasted parts or time, the bearing surfaces were cut on a manual lathe in another step. Using proper speeds, feeds, and a sharp tool, excellent surface finishes were obtained on the piece.

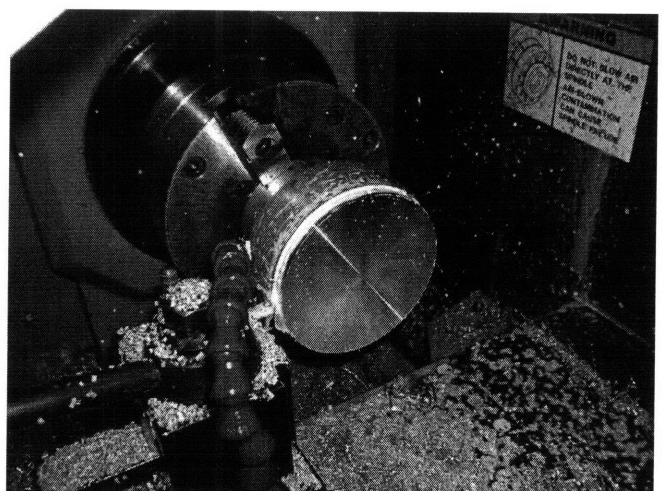

Figure 31: Turning the Inboard Side of the Rear Hubs on the CNC Lathe

Once this part was completed, the second hub was made using the same process. The second part is always easier than the first, as the operator is 100% sure that the CAM code is correct. At this point, the operator can simply hit start and not have to think about the part until the code is completed.

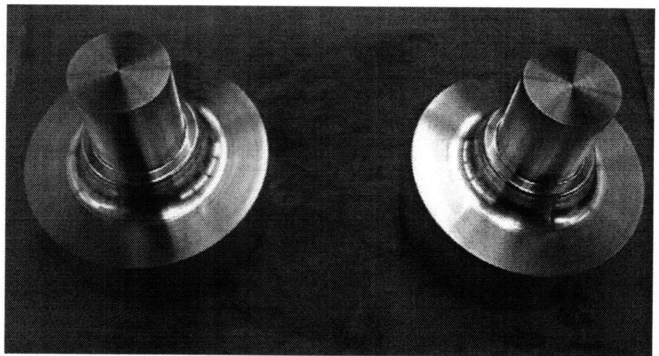

Figure 32: Rear Hubs after Completion of CNC Lathe Work

4.2.2 Manual Lathe Work

It is generally easier to drill holes on a manual lathe as opposed to the CNC since the operator has more feel as to how well the drill is cutting. Therefore, the center hole in the hubs was drilled and then reamed on a manual lathe. This hole is required to interface with the splines on the half-shafts. After being center drilled, and then drilled undersize, the hole was reamed to the specification for the spline, which was a diameter of 0.812"-0.816". The closest reamer available was a 13/16" (0.8125"), well within the tolerance range

Figure 33: Reaming the Inner Bore of the Rear Hubs in Preparation for Splining

The bearing surface was also cut on the manual lathe, as the operator has more control over tolerances. Using a carbide cutter, the surfaces were cut for a 0.003" interference fit with the wheel bearings.

4.2.3 CNC Mill Work

An EZ-Trak was used to drill the holes for the brake rotors, wheel bolts, and drive pins. This operation could all be done from the outboard side of the hub, which decreases setup time. The hubs were clamped to the table using v-blocks as standoffs, and bolted to the table using a single bolt. The center of the hub was set as the zero, and was found using a dial indicator mounted into the spindle of the mill.

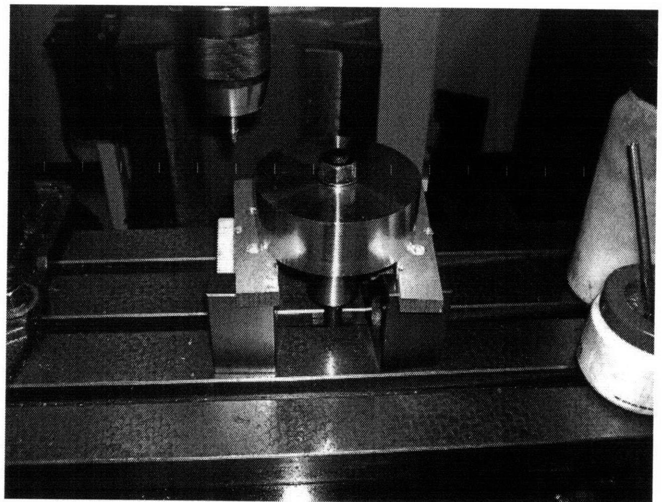

Figure 34: Rear Hub Clamped to the Table of the EZ-Trak Mill Using V-Blocks and Aluminum Standoffs

The holes for the brake rotors and wheel bolts were first center drilled, and then were drilled with a ¼" and 3/8" drill bit respectively. The holes for the drive pins were machined differently. As with the wheel centers, it is critical that they lie in the proper location, so once again an undersized 3/8" endmill was used, followed by a 0.3745" reamer, giving an interference fit of 0.0005", which is more than sufficient for the steel pins. The step was created by then drilling the same location with a ¼" drill bit.

In order to mill the contour into the face of the hub, as well as the recess for the castle nut, a jig was created to hold the hub using the three wheel bolt locations, in order to provide a more rigid clamping system. Once this jig is clamped into the vise of the mill, the hub is bolted to it and the zero is set to be the center of the hub using a dial indicator. A ½" ball endmill was used to cut the castle nut recess, and a flat ½" endmill was used to create the contour.

Figure 35: Cutting the Castle Nut Recess in the Rear Hubs using the Hub Jig Clamped in the EZ-Trak Vice

The last remaining operation was to machine the hex shaped bolt recesses in the inboard side of the hub for the wheel bolts. After pressing in two of the three pins, the hub was placed outboard side down on the table of the mill with the two pins in the channel of the table. By ensuring the two pins are pressed against the channel, the hub can be clocked correctly to drill the holes. The hub was clamped to the table, and the center of the hub was found once again with a dial indicator. Using a ¼" endmill, the hex pockets were created. Unfortunately, a picture of this operation was not taken. After these pockets are cut, the third drive pin can be pressed in.

4.2.4 Spline Broaching

Rockford Acromatic Products has a broaching tool capable of creating a spline to interface with the half-shafts used. Broaching provides an easy yet precise method of spline cutting, and is far superior to EDM. For a reasonable price of $40, Rockford broached the splines in the two rear hubs. The lead time between sending them the hubs and receiving them was upwards of three weeks, so the timing of this process should be worked out such that it holds up production of the rest of the car.

Unfortunately, the packaging that the hubs were sent back in was subpar, with the two hubs able to shift and contact each other. This contact during shipping led to some damage to the hubs, with most being purely cosmetic. A file and sandpaper was able to remove most of the damage, but some dents in the face of one of the hubs were still present. While a $40 broaching service is petty change for a large company such as Rockford, proper packaging should not be an optional service, so this fault should be mentioned in future years to avoid damage.

4.3 Limited Slip Differential

The Torsen Limited Slip Differential is the most complex component to manufacture of the entire driveline, if not the entire vehicle. Not only are there many different components, but these components must all mate together seamlessly with proper tolerances, or else the system will either fail to go together or may even fail catastrophically. The manufacture of each of these components is highly involved, and a manufacturing process was created for each part. This helps to avoid confusion, and most importantly, costly mistakes in the machining process.

4.3.1 Differential Mounting Components

4.3.1.1 Differential Brackets

The differential brackets are a piece that can be created relatively quickly. Two sets were created, with the first set being made of 6061-T6 due to a lack of a source for 7075. Once 7075-T651 was actually procured, a second set was created in one day, with the material being purchased in the morning, cut on the waterjet in the early afternoon, and finished on the EZ-Trak that evening. It is this set of brackets that made its way onto MY08.

4.3.1.1.1 Waterjet Cutting

Just as with the wheel centers, the differential brackets were a good place to utilize waterjet cutting. With the width of the brackets being ¾", ¾" plate was an obvious choice. Since 7075-T651 is more expensive than 6061, only enough material was bought to waterjet the two brackets. A 12"x12" piece was purchased for $185 from Admiral Metals, which provided just enough material for both brackets to be cut from the same sheet.

Since it is imperative that the plate doesn't shift, the plate was secured well in the waterjet utilizing the lead bricks. The brackets were cut at quality 3, and took approximately 40 minutes to cut. The holes for the eccentrics and for mounting were not cut on the waterjet, as the tolerances required were higher than what the waterjet can confidently cut.

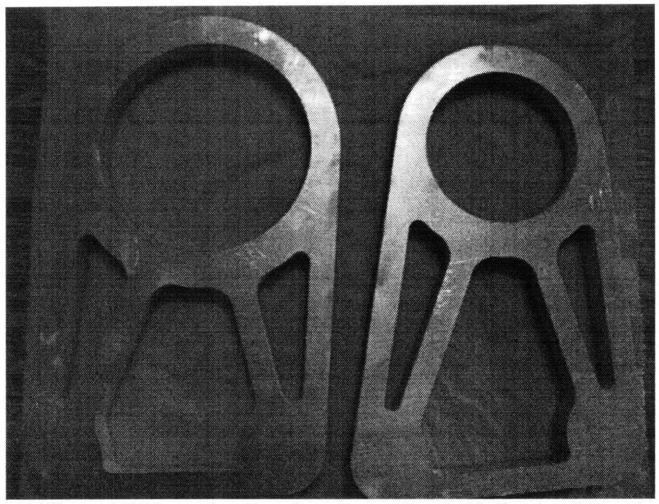

Figure 36: Differential Mounting Brackets Immediately Following Waterjet Cutting

4.3.1.1.2 CNC Mill Work

Since the waterjetted brackets were too large to fit into the vice properly, they were clamped onto the table. Elevating them on two ½" spacers, and clocking them properly using two pins inserted into the channels of the table, they were clamped to the table utilizing a single clamp which spread the clamping load over the entire width of the bracket.

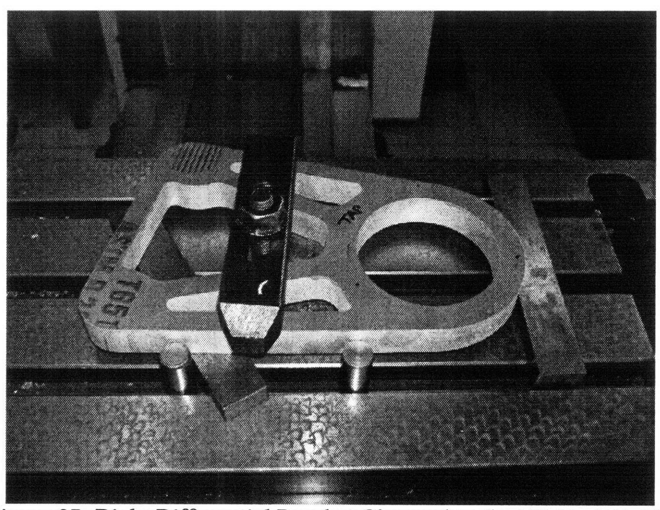

Figure 37: Right Differential Bracket Clamped to the EZ-Trak Table

The zero was set at the center of the hole for the eccentric using a dial indicator inserted into the spindle. These holes were then milled to the proper size using a ½" endmill. The three bolt holes for attaching the eccentrics were also drilled, then tapped for a 10-24 cap-head bolt.

Although the design called for 'footballs' to be used to aid in chain tensioning, the footballs were initially not cut. The possibility existed for the eccentrics to have sufficient chain tensioning ability, thus the fit of the differential brackets sans footballs was first checked. These two ½" holes were drilled in this setup on the CNC mill. Upon final assembly, the chain tensioning was well within the range of the eccentrics, so the footballs were not needed.

4.3.1.2 Eccentrics

Since the eccentrics utilize a hole that is non-concentric with the outside of the piece, the hole cannot be cut on a lathe. Therefore, after the initial lathe work to create the shape of the eccentric, the piece is finished on a CNC Mill. Since the diameter of the larger eccentric is more than 5", the same 7075 stock used for the hubs and differential carrier could not be used. Unfortunately, 7075 was unavailable in the size needed, so 2024 was used as an acceptable substitute. Both the left and right eccentrics are identical except for size, thus require basically the same manufacturing process.

4.3.1.2.1 Manual Lathe Work

After cutting the stock to size on a horizontal band saw, it was turned to the proper size and shape on a manual lathe. There was nothing tricky here, besides ensuring that proper tolerances were held to mate with the differential brackets.

4.3.1.2.2 CNC Mill Work

With the part cut to size, the center hole and the mounting holes were cut. With the piece clamped in the vise of the mill, the zero was centered in the piece using a dial indicator in the spindle. The mounting holes were center drilled and then drilled using a #10 drill bit.

The center hole was cut using a ½" endmill. It is important to note that if the part is clamped too tightly, as material is removed from the center the piece will compress inward, out of round, which could negatively affect the function of the eccentrics. It is imperative to make sure that a rigid setup is used, but does not apply too much clamping force onto the piece. Alternatively to clamping the piece in the vise, it could have been securely clamped to mill table. This setup would probably have been ideal, and is recommended for future work.

It is also a good idea to put a timing mark into both eccentrics in the same location, so that they can both be clocked together properly. This was done by cutting a small notch into the side of the mounting face using a ½" endmill, denoting the zero degree position.

Figure 38: Milling the Inner Bore of the Left Eccentric, Using an EZ-Trak

4.3.1.2.3 Bearing Installation

After the machining of the eccentrics is completed, it is an easy step to press in the bearings. After applying some Loctite® bearing retainer, the bearings were pressed in using a hydraulic press. After making sure that the press starts so that the bearing is going in properly, the bearing is pressed in until it contacts the retaining lip on the back side.

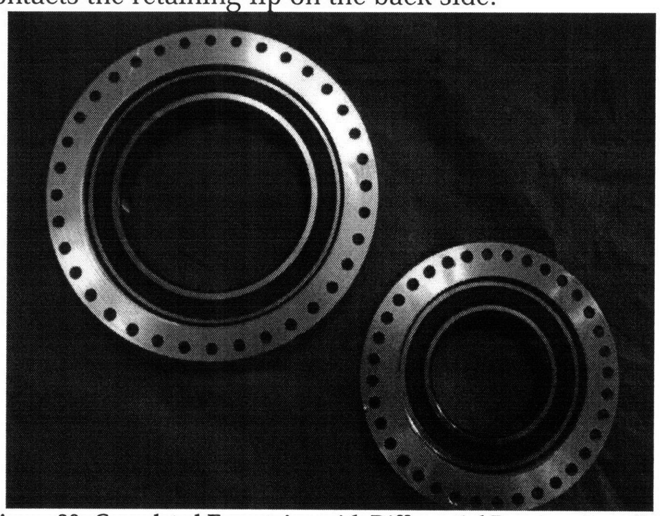

Figure 39: Completed Eccentrics, with Differential Bearings Installed

4.3.2 Drive Components

4.3.2.1 Sprocket

The 7075 48 tooth sprocket comes with a center bore already present. After clamping the piece to the table of the mill using standoffs to avoid cutting into the table, the zero is set to the center of the sprocket using a dial indicator and the center bore of the sprocket.

Using a center drill and ¼" drill, the 8 sprocket mounting holes were drilled. Following that, the spokes were cut into the sprocket using a ½" endmill, and the center bore was enlarged using the same tool.

Figure 40: CNC Milling the Sprocket on an EZ-Trak

4.3.2.2 Input Bell

The input bell is created in three operations on two different machines. First the shape is created on a manual lathe, and then the sprocket mounting holes are cut on a CNC Mill.

4.3.2.2.1 Manual Lathe Work

The two sides of the input bell were created in two setups on a manual lathe. The sprocket side was cut first, using the cut sprocket to make sure the mounting lip is the proper size. The lip is important in load transfer, and if it is too large the part may fail. After ensuring that the sprocket fits correctly, the inner bore is created on the sprocket side.

The piece is then reversed in the lathe, and the inboard side is cut. This process is relatively straightforward, with the angle easily created using the third axis of the lathe.

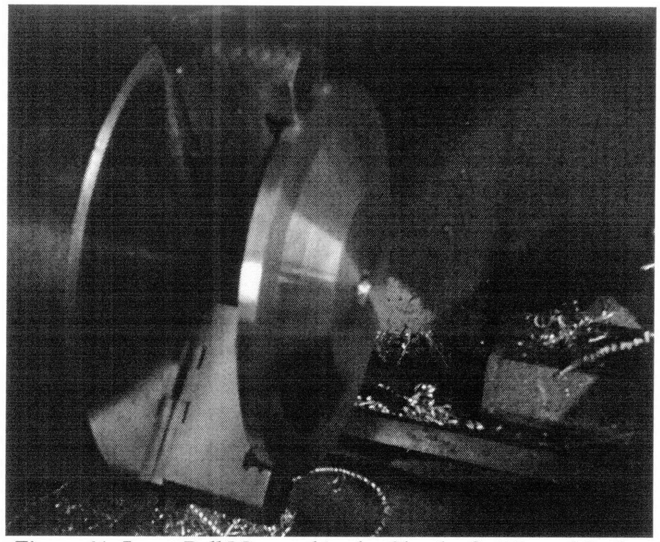

Figure 41: Input Bell Mounted in the Chuck of a Manual Lathe

4.3.2.2.2 CNC Mill Work

Drilling the sprocket mounting holes is relatively straightforward. The piece is clamped using a v-block in the vise, and the zero is set at the center of the piece. The sprocket mounting holes are then center drilled, and then drilled with a ¼" drill. The drive pin holes are not drilled at this time. They were drilled when the holes for the drive pins and helicoils were drilled in the differential housing. This was done to ensure concentricity between the differential housing and the input bell and sprocket. Even the slightest bit of off-axis rotation could lead to excess stress on the housing and failure of components.

4.3.2.2.3 Assembly

The sprocket was then mounted to the input bell using AN4-7A bolts, torque to 15 ft-lbs.

4.3.3 Differential Housing

4.3.3.1 Differential Carrier

The differential carrier is by far the hardest of all driveline components to manufacture, requiring multiple complicated setups, tight tolerances, and complex CNC work. The manufacturing processes described here are highly detailed and contain many pictures, with the goal of aiding future team members in the process of differential manufacturing. While these steps and photos are very detailed, there are still many subtleties that are not mentioned in the text or images that must be considered when undertaking a project such as this.

The manufacturing process outlined here is in five steps, beginning with basic roughing work, followed by CNC lathe, CNC Mill, Manual Lathe, and additional CNC Mill work. Each of these processes are described in detail in the following sections.

4.3.3.1.1 Rough Work

The stock used for the differential carrier is the same 5" OD 7075-T651 stock used for the hubs. The first step was to cut the long bar of stock to length using a horizontal bandsaw. The stock was cut slightly oversize, such that the ends could be made flat and perpendicular on the lathe, without the chance of removing too much material and ending up with a piece of stock that is too short. When cutting a bar with a diameter this large, it is important to take all precautions necessary to avoid 'walking' of the blade, or rather having a cut that is not perpendicular. This can be avoided by ensuring the blade is tight, the blade guides are as close to the work piece as possible, and the cut is not performed too quickly. While making the cut, it is also necessary to ensure that the blade receives enough wax and coolant.

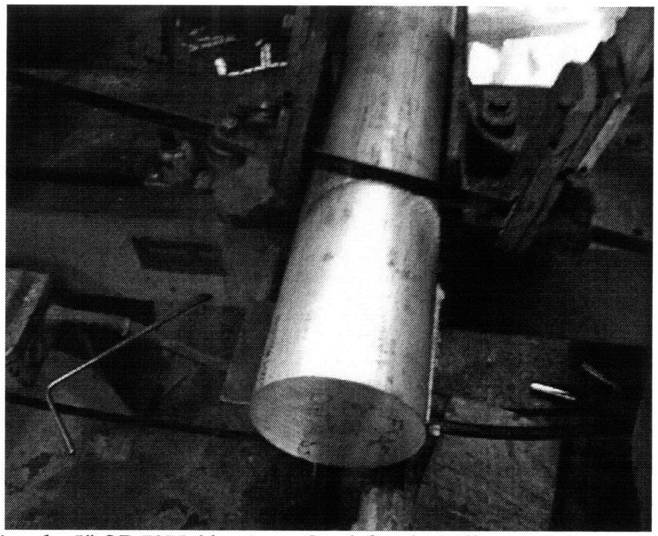

Figure 42: Cutting the 5" OD 7075 Aluminum Stock for the Differential Center Section to Length

4.3.3.1.2 CNC Lathe Work

With the bar of stock cut slightly oversize, it is then taken to the CNC lathe to cut the profile. Generally, there is no reason to do the CNC lathe work prior to doing the CNC mill work, or visa versa. However, it is much easier to ensure that tolerances are being kept on the CNC mill, since it is much easier to get a measurement when drilling and making cuts. On a couple occasions in the past, the CNC lathe has unfortunately cut surfaces too small, thus making the parts useless. Since a heavy amount of time would be invested in the CNC mill work, cutting the profile to too small of a diameter would be devastating to the project. In order to save the headache of possible failures, the CNC lathe work was the first process completed.

Since both sides of the differential carrier have splines that require cutting on the lathe, it is impossible to make both profiles on one setup. Therefore, on side must be cut first, the part must be flipped in the chuck, and the other side cut. The drive side of the carrier was cut first, as when flipped there would be more material to clamp in the vise, making for a more secure setup. The he profile was cut to about the midpoint of the final carrier, such that if there was any difference in OD of either the first or second cut, the difference would lie in the center of the piece, where it would not affect the sealing of the case. In the case where there was such a discrepancy, the o-ring grooves could be cut accordingly to ensure a proper seal was made. Additionally, the bearing surfaces on each side of the housing were left oversize by 0.100", such that they would not be marred during the rest of the manufacturing process. They were later cut to size in the final step of the manufacturing process.

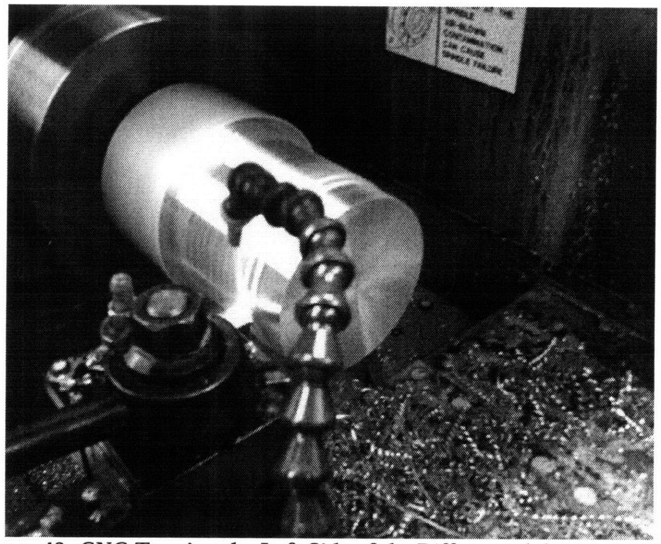

Figure 43: CNC Turning the Left Side of the Differential Center Section

After cutting the drive side profile the part was rotated in the chuck, clamped by the drive side bearing surface. The piece was center drilled such that a live spindle could be used while turning the profile, helping to improve the stiffness of the setup. With everything clamped down tightly, the profile was cut.

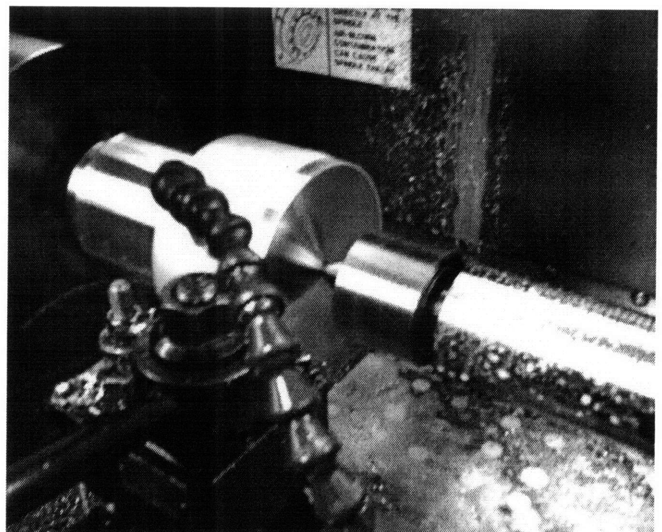

Figure 44: CNC Turning the Right Side of the Differential Center Section

When supporting a part using the tailstock and a live spindle, it is imperative to check the G-code to ensure that the tool would be clear of the tail stock at all times. Crashing the tool into the part, spindle, or tailstock is the last thing that any CNC machinist, or hardworking student, wants to see.

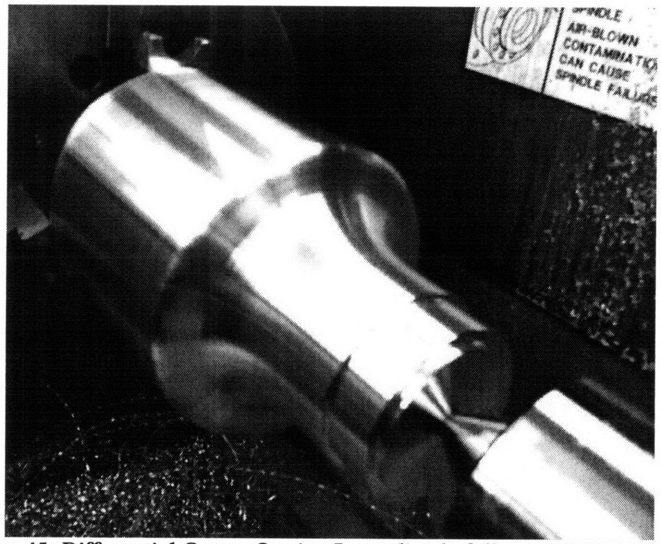

Figure 45: Differential Center Section Immediately following CNC Turning

4.3.3.1.3 CNC Mill Work

With the profile of the differential carrier cut, the next step was to create the windows and pin holes for the element gears. This was done using an EZ-Trak and a rotary vice. The windows and pin holes are projected from a plane tangent to the circular carrier, so complex milling is not necessary. One set of holes and pockets can be cut, the part can be rotated by a set amount of degrees, and the next set can be cut. In previous iterations of the MIT Motorsports differential, a manual rotary vice was used. This method was proven to create a part that was well within the range of tolerances, and could have been used again. However, the Edgerton Student Shop had recently acquired a computer controlled rotary vice made by Centroid®, capable of an angular accuracy of 0.001 degrees. This rotary vise can be programmed to act as a fourth axis, or could be used in manual mode where the operator chooses what angle to rotate the piece by. The manual mode was perfect for this application, and yielded excellent results.

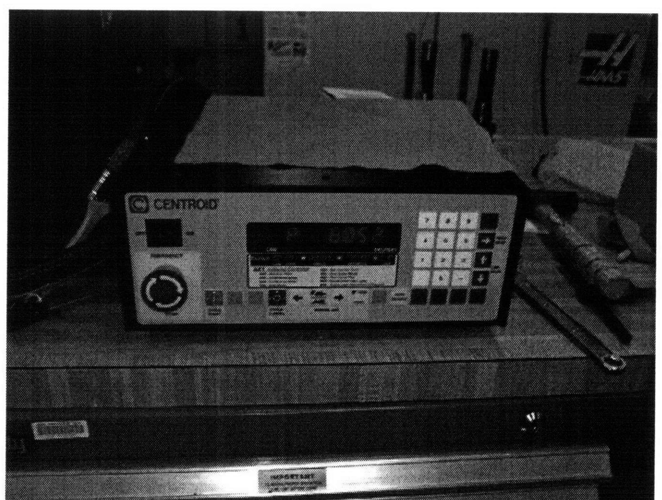

Figure 46: Centroid® Rotary Vise Controller

With the rotary vice clamped securely to the table of the mill, the differential carrier was clamped with a chuck on the driven side, and was supported with a live center on the opposite side.

At this point, it is imperative to ensure that the piece and the vice are oriented correctly in reference to the milling head. This means that the part must be concentric with the chuck, and the entire rotary vise system must parallel to the x-axis of the mill, and perpendicular to the y-axis. These properties can all be checked using either a dial indicator fixed to the table of the mill, or in the spindle.

With the high precision of the rotary vice, the manufacturing time can be reduced through the reduction of tool changes. With the manual rotary vice, there was some level of error in rotation, so rotating the part as few times as possible was a priority. With the computer controlled rotary vise, instead of rotating the part to a certain angle and performing all operations necessary at that angle, requiring multiple tool changes, the part can be rotated with a high level of accuracy such that all operations at multiple angles can be performed using a specific tool, and once those operations are completed the tool can be changed and all operations at all angles requiring that tool can be performed. This greatly increases productivity and decreases manufacturing time.

Figure 47: Differential Center Section Clamped in the Rotary Vise, with a Dial Indicator Used for Alignment

Once the part was properly oriented in the rotary vise and on the table, zero was set both on the rotary vice and the EX-Trak. When the rotary vice was turned off, the zero would be lost, so it was necessary to either never turn the controller off, or before doing so rotating the part back to the zero position.

The first step in the milling process was to drill the holes for the journal pins. Since the holes are not perpendicular to the surface of the piece, and lie on a curved surface, attempting to use a center drill followed by a drill would more likely lead to walking of the bit and drifting of the hole. There are two ways to avoid this. The first is to use a spotting drill. This method was used in the manufacture of previous MIT Motorsports differential housings with great success. Alternatively, an endmill can be used to create a flat face for the drill bit. A ¼" endmill was used to mill a circle slightly larger than the drill bit to be used, essentially creating a pocket for the drill bit to follow. This method, while simple, proved to be successful.

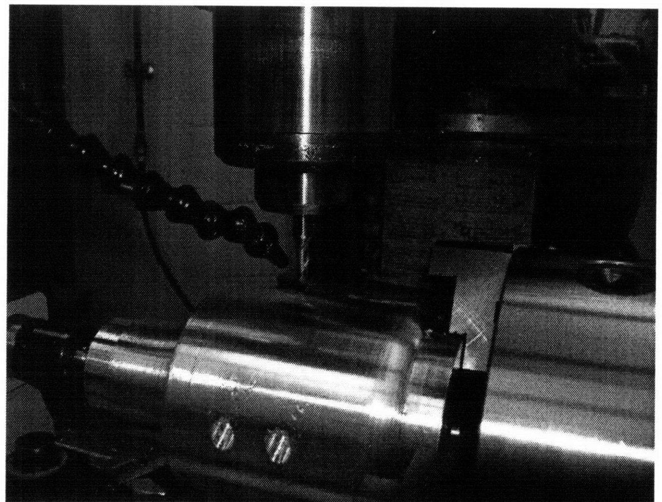

Figure 48: Cutting Flat Faces in the Differential Center Section before Drilling the Journal Pin Holes

One the flat was created, the holes were center drilled and then drilled to the correct depth. Torsen specifies associated tolerances with their cast differential housing, so these journal pin holes were reamed to specification.

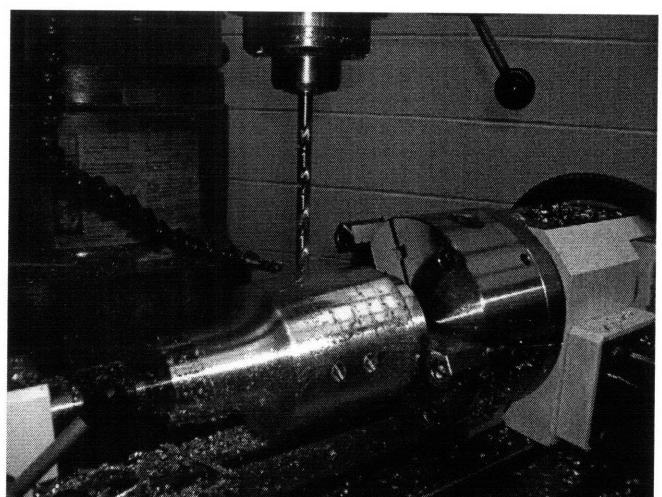

Figure 49: Drilling the Journal Pin Holes

Following the drilling of the journal pin holes, the element gear windows were cut. A half-inch four-flute endmill was used to create these pockets. Since the windows require cutting nearly two inches deep, it is necessary to ensure that a cutter with enough cutting length is used. For this step, a single roughing cut was used, with a finish pass only at the final depth. As with the other operations, once one window was cut the part was rotated, and the other windows were then cut.

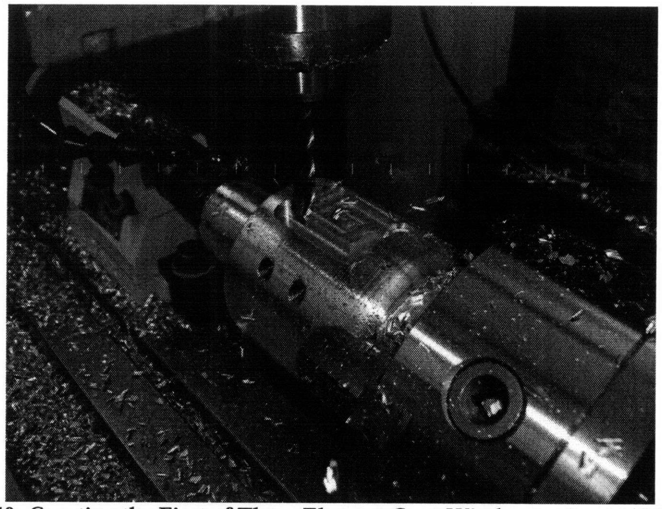

Figure 50: Creating the First of Three Element Gear Windows using a ½" Endmill

The next step on the rotary vise is to drill the holes for the pins that will restrain the journal pins. This process is very similar to the drilling of the journal pin holes, as first a flat must be created with an end mill, followed by a center drill and the properly sized drill bit. The final step was to drill the single hole which would contain the ¼" dowel pin used to restrain the movement of the sealing sleeve.

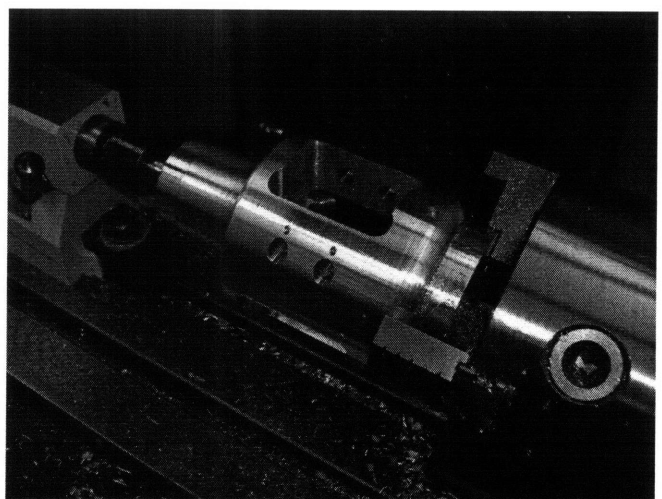

Figure 51: Differential Center Section after the Completion of all CNC Milling Operations

4.3.3.1.4 Manual Lathe Work

The next step of the machining process was to finish the internals of the differential carrier, which was done on a manual lathe. The part was clamped into the chuck on the bearing surfaces, and was checked for concentricity. A six-jaw chuck was used, since was the only one available at the Edgerton Student Shop which had the three adjustment screws on the sides of the chuck which can be used to adjust the concentricity of the clamped part. By loosening or tightening these adjustment screws, the concentricity of the chuck can be adjusted such that the part spins concentrically. Using a dial indicator mounted to the ways of the lathe and contacting a point on the part, the chuck was manually rotated to check for concentricity. By tightening and loosening the adjustment screws, the part was brought to within 0.0005" of round, which was thought to be more than acceptable.

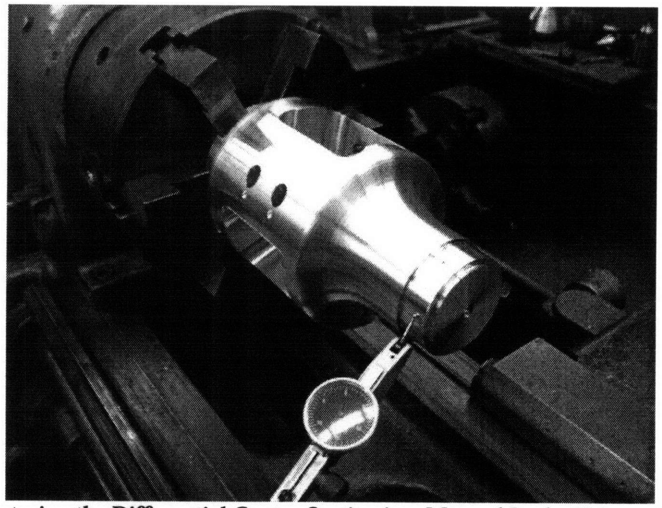

Figure 52: Centering the Differential Center Section in a Manual Lathe Using a Dial Indicator

Since a live center could not be used to support the free end of the part, speeds and feeds were reduced greatly in order to limit the chance of the part deflecting, or in the worst case scenario, being thrown from the lathe while cutting.

The first step to finishing the internals of the carrier was to create the bore through the entire piece. A hole was first drilled, and this hole was enlarged using a boring bar to enlarge the hole to the proper diameter. In addition to the center bore, the bearing surfaces for the half-shafts were also created.

Figure 53: Drilling the Center Bore of the Differential Center Section

The design requires that a circular recess for the washers be cut into the inside of the housing. The only way to create this recess is to use a long boring bar with a long cutting tip. The length of the boring bar is necessary such that the boring bar can actually extend through the piece up to the surface to be cut. The circular recess has a diameter larger than that of the inner bore of the piece, so the longer length of the cutting tip is necessary such that the side of the boring bar does not contact the inner bore of the differential carrier.

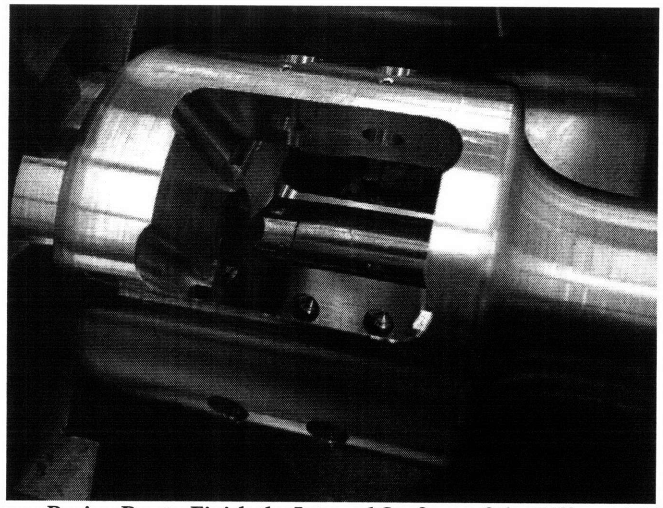

Figure 54: Using a Boring Bar to Finish the Internal Surfaces of the Differential Center Section

Once the recess is created on one side, the part can be flipped, checked once again for concentricity, and the recess can be created on the other side.

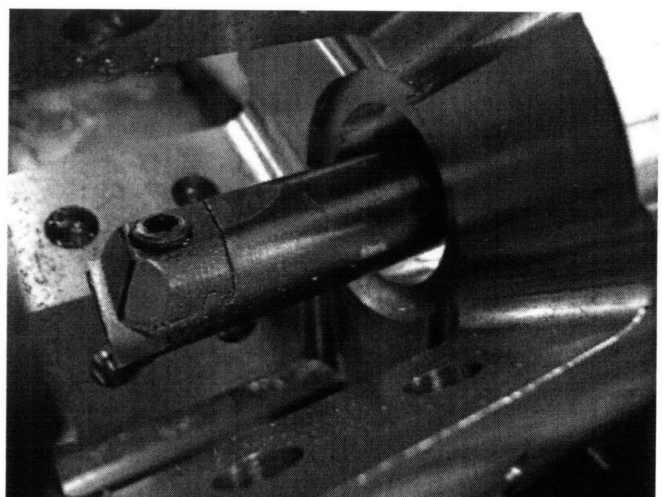

Figure 55: A Closer Look at the Boring Bar, and a Finished Internal Face of the Differential Center

The o-ring grooves were also created on the manual lathe. Luckily, a grooving tool of the exact width needed for proper o-ring expansion was found, simplifying the manufacturing process. After locating the grooves, the grooves were easily cut to the proper depth. Lots of coolant and a slow feed were used to ensure they were cut properly without causing deflections or chatter.

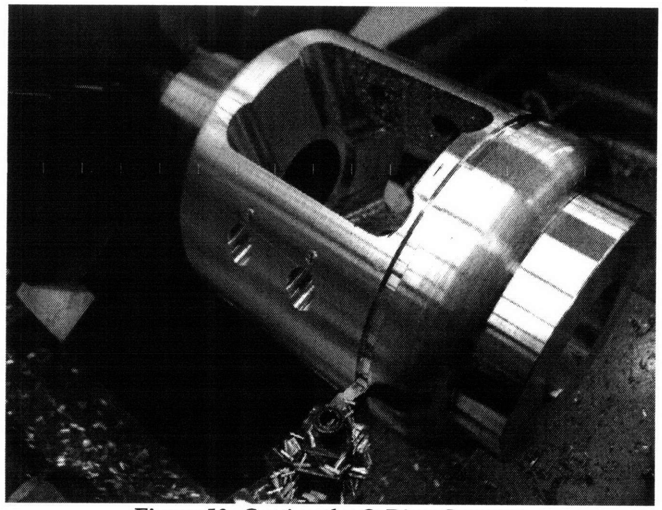

Figure 56: Cutting the O-Ring Grooves

The last step on the lathe was to turn the two bearing surfaces down to the proper size, which was a straightforward process using a sharp carbide cutter. After the first surface was cut, the part was rotated and clamped in the chuck, but care was used to make sure the bearing surface was not marred or damaged in any way.

Figure 57: Finishing the Bearing Surfaces of the Differential Center Section

4.3.3.1.5 Additional CNC Mill Work

The part was then clamped back into the EZ-Trak on end such that the mating surface to the sprocket could be finalized, with the drilling of the hole for the drive pins and the helicoils. Using a v-block and tall jaws, the differential carrier was clamped with the drive side up, and a dial indicator in the spindle was used to set the machine zero. While clamping the piece in this orientation, it is important to make sure that it is sitting flat in the vise, and that the v-block or jaws are not marring the surface.

Figure 58: Differential Center Section Mounted in EZ-Trak Vise for Drilling Bolt and Pin Holes on Input Face

With the piece securely clamped and the zero set, the three bolt holes for the input bell are drilled and tapped. The holes are tapped using the bottoming tap included in the Heli-coil® set. While the bolts to be used to fasten the input bell to the differential carrier are 5/16", the tapped holes in the carrier are larger than 5/16", such that they can accommodate the Heli-coils.

Figure 59: Tapping the Differential Center Section for Helicoils

The Heli-coils are easily inserted into the newly tapped holes using the provided insertion tool, and a tap handle. This tool is relatively straightforward to use, with its purpose being to serve as a guide for the Heli-coil, ensuring that it threads in properly.

Figure 60: Installing the Helicoils on Input Face

With the mounting holes tapped and Heli-coils inserted, the input bell was bolted to the top of the differential carrier, so that the holes for the drive pins could be drilled and reamed. These holes are drilled simultaneously in both parts, basically guaranteeing that the pieces will fit together properly once the drive pins are pressed into the carrier.

One of the bearings used to support the half-shafts was used to ensure concentricity between the input bell and the carrier, since it is imperative that these two components remain concentric. With the bearing inserted and taped off from dirt and shavings, the three drive pin bolts were center drilled, drilled, and then reamed to the proper size to accept the 3/8" steel dowel pins.

Figure 61: Input Bell Mounted to the Differential Center Section, Using Stub-Shaft Bearing to Ensure Concentricity

4.3.3.1.6 Finishing and Final Steps

Following all of the machining work, only a few small steps remain in the fabrication of the differential carrier, which are all done by hand. Since CNC Milling can lead to sharp edges, and edges with burrs, sandpaper was used to break these edges and burrs. This was done for two reasons. The first was so that the burrs would not cut or mar the sealing sleeve upon insertion.

The second was to save the hands of the person installing the gearing into the carrier. The carrier is a small space, and inserting the gears can be difficult, and the last thing someone needs is a cut on their hands while assembling.

The outside surface of the carrier was also sanded, and some polishing compound was used as well. This was done for two reasons, with the first being to remove all scratches from the mating surface between the sleeve and the carrier to reduce the possibility of leaks. The second reason was purely cosmetic; race-car components can be functional and good looking.

The final steps taken on the differential carrier before the gearing was installed was to press in the three 3/8" drive pins and the ¼" sleeve retention pin on an arbor press.

4.3.3.2 Sealing Sleeve

The sealing sleeve was one of the easier components to fabricate, requiring only simple lathe work and mill work. Schedule 40 aluminum pipe was selected for the sleeve. Since the sleeve is not a structural component, it is not necessary to have a high strength piece of aluminum, so simple 6061 pipe will work well. The sleeve was first cut to size from the one foot section that was purchased, on a horizontal band saw. After that, a manual lathe was used to turn the ID and the OD to the proper size. Following this, the slot for the ¼" retaining pin was cut on the mill, and the hole for the AN plug was drilled and tapped. All the edges were also sanded, in the hope of reducing the possibility of cutting the o-rings when pressing on the sleeve.

Figure 62: Cutting the Schedule 40 Pipe to Length

4.3.3.3 Thrust Washers

The final component required for the Torsen style limited slip differential was the steel thrust washers. Luckily, there were six washers which had already been partially fabricated in a previous year. The holes were drilled and reamed in the 0.095" thick steel stock, and they were cut roughly to size.

The only machining step required was to mount them in the vise of a CNC Mill using a jig created specifically for this process for the 2005 vehicle. Once the jig was mounted in the vise of the mill, and the blanks were bolted to the jig, a ¼" endmill was used to cut the profile.

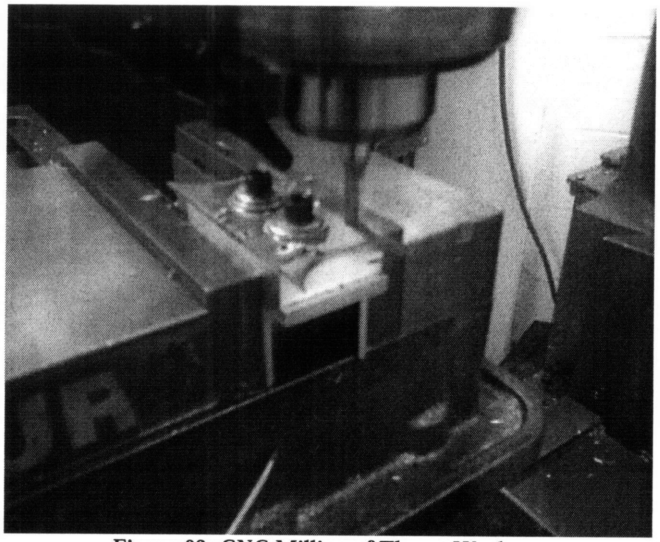

Figure 63: CNC Milling of Thrust Washers

Once the profiles were cut on the mill, the last remaining step was to get the parts surface ground to 0.0625". Although 0.030" is generally a large amount to surface grind, the reason for originally going with 0.095" thick stock was the lack of availability of anything close to the final dimension. While stock of the proper dimension could have been obtained this year, it was decided that the cost savings associated with grinding thinner material was not worth the time savings that were had by using the already half-completed washers that were in stock. Grinding was performed at the MIT Central Machine Shop.

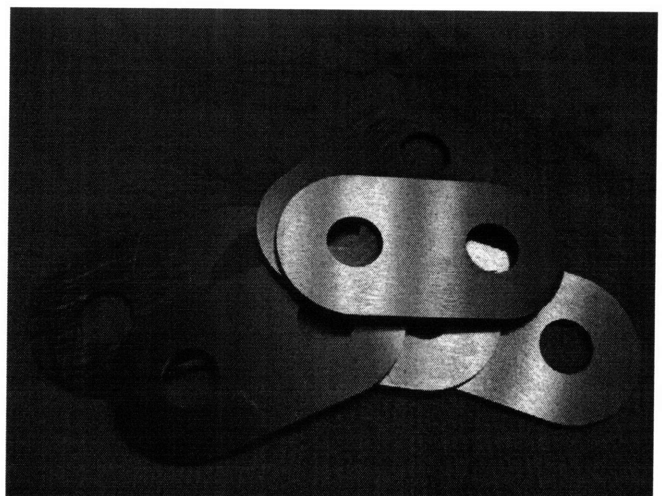

Figure 64: Thrust Washers after being Surface Ground

5.0 Final Assembly

5.1 Wheel Centers

As mentioned previously, AN4-10A bolts were used to fasten the wheel centers to the aluminum Keizer wheels. Using a bolt torque chart to check the proper torque, the bolts were tightened to 15 ft-lbs, in a crisscross pattern to ensure proper seating. After mounting the wheel centers, the outers were checked for proper seal, and tires were mounted to the wheels. Goodyear Eagle tires were used for the slicks, and Hoosier tires were used for the rains.

5.2 Rear Hubs

Using a hydraulic press, the rear hubs can be pressed into the uprights. First, the wheel bearing was pressed onto the hub, using Loctite bearing retainer to add additional strength to the already high press fit. The hub and bearing assembly was then pressed into the rear upright, once again using some Loctite.

With the upright and hub firmly together, the upright was bolted to the vehicle suspension, 3/8" AN bolts were inserted into the hubs for wheel bolts, and the wheels were able to be mounted to the vehicle.

5.3 Limited Slip Differential

The half-shaft bearings were simple to install, and were pressed in using a hydraulic press. The drive side eccentric was also pressed onto the carrier such that it could be mounted to the left differential bracket and input bell, and chain tension could be checked in order to determine whether footballs were needed as an additional chain tensioning method. As was discussed earlier, chain tensioning with the eccentrics was deemed to be sufficient, so the footballs were not seen as necessary.

The internal gearing of the differential were then assembled and installed into the differential carrier. The steps for gear assembly and timing outlined in Keith Durand's undergraduate thesis were highly detailed and made assembling the gearing an almost trivial task. Since his steps were so thorough, the steps for gear assembly are not described here.

Figure 65: Differential Center Section with all Internal Components, including Gears, Washers, and Thrust Washers

Once the gearing is installed, it is very straightforward to check whether all the gears were properly assembled. By inserting a half-shaft into one end of the differential and turning it, the gears should all rotate freely when the element gears are lubricated. If any binding is occurring, the differential should immediately be checked for proper gear timing.

Figure 66: Differential Center Section with Gearing Installed and Left Eccentric and Bearing Pressed

The two Viton o-rings were then installed into their respective grooves on the differential carrier, and the sealing sleeve was pressed on. The o-rings require a high amount of force to compress, so a hydraulic press was used to press on the sealing sleeve. When pressing on the sleeve it is important to go slowly and methodically to ensure that the o-rings are left intact, as even the smallest nick will lead to leaks. The two shaft seals were then pressed into the two ends of the differential housing. After these seals have been installed, it is important to make sure that the seals are not cut or nicked in anyway, with even the smallest of cuts leading to failure of the seal.

The right side eccentric was then pressed onto the carrier in identical fashion to the left side eccentric. The eccentrics were both bolted to the differential brackets using three 10-24 ½" bolts each. Loctite should be used on these bolts to ensure that the eccentrics stay tightly bolted to the brackets. The entire bracket/housing assembly was then bolted onto the vehicle using two ½" bolts to mount to the engine, and two 7/16" bolts to mount to the frame tabs.

Figure 67: Differential Assembly Mounted on Frame Following Powder Coating

The input bell and sprocket were then installed. Three AN5H-7A bolts were used to bolt the input bell to the differential carrier, and were safety wired for positive retention. After bolting the 12T sprocket onto the engine, the chain can be installed. Using a chain tool, the two ends of the chain were attached together. Alternatively, a master link can be used. If a master link is not used, like in this case, it is necessary to make sure that when the chain pin is un-pressed and then pressed back in that the chain maintains its flexibility of motion. If flexibility is lost, the pin should be un-pressed, and then pressed again.

5.4 Axles and Shafts

When inserting the half-shafts into the differential housing, it is extremely important to do so carefully, and not cut the seals with the splines of the shafts. After inserting the splines through the seals, the half-shafts were inserted deeper into the housing until contacting the element gears. After rotating the shaft slightly to ensure that the spline meshes properly with the element gear splines, the half-shaft was pushed in further, with a retaining ring in the end of the shaft locking into place in the element gear. A mallet may be needed to ensure that the ring locks in place. If the ring lock is seated properly, the stub-shaft will not move axially by hand.

Installation of the axle into the hubs is straightforward, with the splines of the axles meshing with the splines in the hubs. After putting the spacer onto the half-shaft, and inserting the half-shaft into the hub, a washer and castle nut clamp the part together.

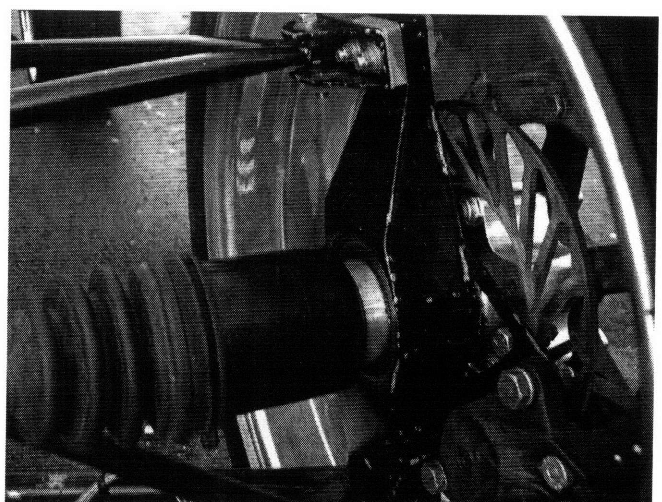

Figure 68: Inboard view of the rear right corner

The axles cannot be installed if the suspension is completely bolted together, so it must be temporarily disassembled to insert the axle. The upper a-arm bolt on the upright was removed, and the push rod was extended, giving enough clearance to insert the axles into the two half-shafts. The suspension was then reattached, and the retaining rings for the axles inserted into the half-shafts. The protective boots for the axles were then fastened to the axle and half-shafts using cable ties.

5.5 Lubrication

The differential case was filled to two-thirds capacity using Spectro® 75w140 full synthetic differential gear lube. The oil level can be dropped during the endurance race in order to help protect against leaking. While having less lubrication will accelerate wear, not leaking and finishing endurance is a priority.

The AN fill plug was wrapped with Teflon tape, and was threaded into the hole in the sealing sleeve. A good amount of tripod joint grease was used in the half-shafts and axles to lubricate and protect the tripod joints.

6.0 Testing

As with every mechanical design and system, adequate testing should be utilized to ensure components will behave as anticipated. Additionally, when designing components for Formula SAE it is important to ensure that components that can fail will fail before competition, with enough time to replace them. The last thing a team wants is to be taken out of contention due to some problem that could have been addressed through testing.

At the time of publication of this document, the MIT Motorsports MY08 vehicle has been tested for a few hours. While the vehicle has not yet had a significant amount of driving time, initial testing sessions have proven to be promising. As would be expected, the system has performed well under acceleration, cornering, and braking. The system has even withstood the abuse of repeated hard downshifts where revs were not matched properly.

The differential has shown some leakage from the right side interface between the differential housing and the sealing sleeve. Disassembly showed that the right side o-ring was gouged by the slot for the retention pin during installation, leading to the leak. This problem was remedied by taking a file and sandpaper to the edges of the slot, as well as creating more of a ramp on the edge of the sleeve in order to reduce the likelihood of damaging the o-rings once again.

Upon disassembly, the housing was observed to have been breaking in well. The aluminum housing was intact, and only trace amounts of metal wear particles were evident in the oil. These particles are to be expected during initial break in, and are due to the contact between the thrust washers and the element gears.

Due to unfortunate circumstances, MY08 did not travel to Virginia for Formula SAE VIR. However, the team is currently prepping the car and looking forward to competing in Detroit in the coming week. With the results seen in testing sessions to date, there is a high level of confidence that the driveline will hold up well during the Formula SAE competition.

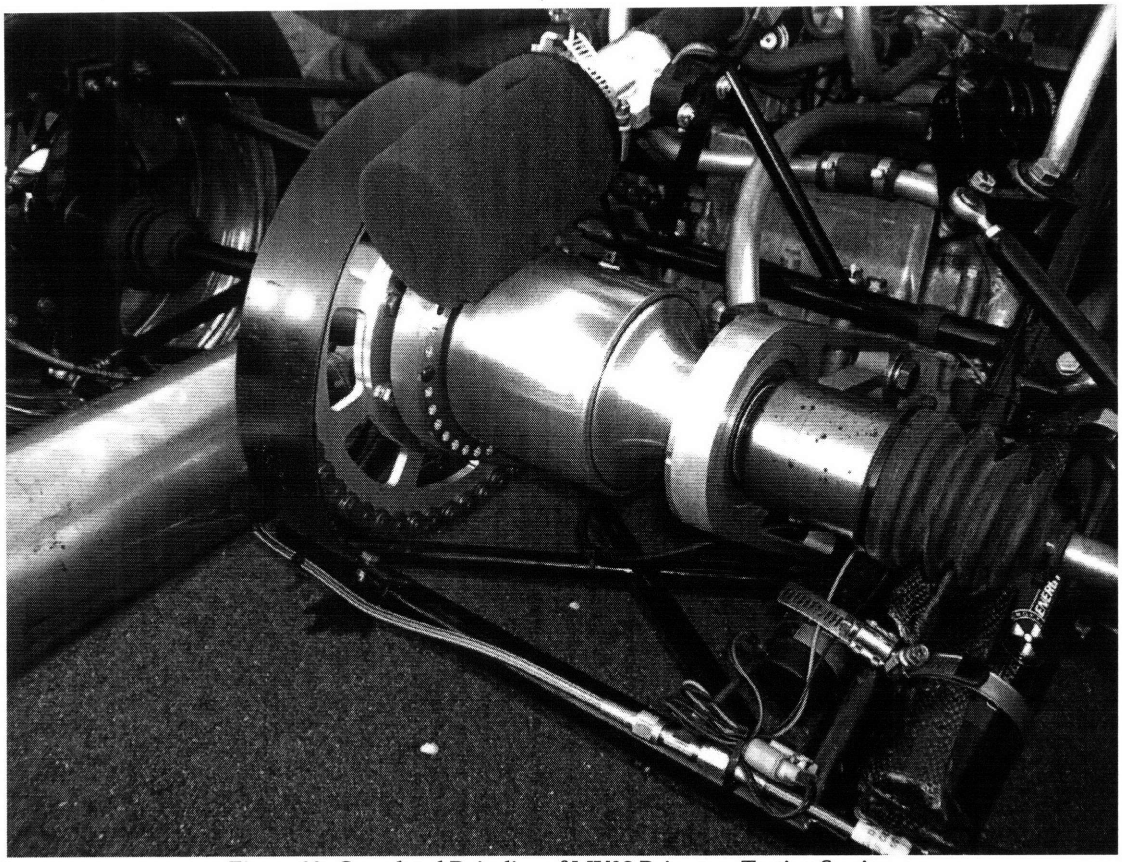
Figure 69: Completed Driveline of MY08 Prior to a Testing Session

7.0 Conclusions

The Formula SAE vehicle driveline presented here appears to meet the intended goals of weight savings, better use of tooling and facilities, and better integration with other vehicle components. The design was an iteration of previous driveline and differential designs and benefitted from the knowledge and advice of past designers. The design was well documented with the intention of keeping this documentation within the MIT Formula SAE team to facilitate driveline design and manufacturing in future years.

The driveline design detailed in this document focused on all of the components needed to transfer power from the engine to the rear drive wheels, and includes the custom limited slip differential housing, drive shafts, hubs, and wheels. Design requirements were determined, components were modeled, loading scenarios were calculated, finite element analysis was performed, and FEA results were used to modify and improve designs. This iterative design process allowed for the optimization of components and removal of excess weight. Following the completion of designs, thorough manufacturing processes were developed, stock was purchased, and components were manufactured. It is also important to note that machinability and manufacturability must always be considered in the design process, especially when designing components that are to be manufactured by student machinists. Innovative designs that cannot be manufactured are as useless; a design must be functional as well as manufacturable.

As with any mechanical design, there is always room for improvement. The design presented here is a very good iteration from those used on MY06 and MY07, but there are still some changes that could be made to improve the overall package. First, other options for wheels should be investigated. It is desirable to find a wheel option that allows for mounting of the wheel center from the inboard side of the wheel while and also allows for a decreasing of overall hub thickness. Secondly, the FEA presented here is generally thorough, but a more detailed analysis may lead to good improvements on all driveline components. Some loads were ignored, others were estimated, and results were not meticulously analyzed. Better FEA can lead to better designs.

In regards to the differential, there are some improvements that can be made in the future. The design presented here is generally a more refined version of the differential originally designed for MY05. While there may not be many visual similarities, the fundamentals of the design are very similar, and the MY08 design leaves little room for improvement. Although the current design performs well, it may be time to look for a new and radical differential design. The Torsen University Special was used for this design, but the Torsen Type 2 differential looks promising. Additionally, there are other manufacturers that make suitable limited slip gearing.

Should the team decide to simply iterate upon the design presented here, a couple suggestions should be considered. First, the differential center section should be redesigned and modified such that the gearing is centered better. The current design leads to a 14" drive shaft on the left and a 15" drive shaft on the right. While this difference is not significant enough to lead to torque steer, reducing part count is always a step in the right direction. Also, with the discontinuance of the Rockford FSAE Kit, the team may find itself switching to the Taylor Race

Axle Kit. This switch would require a new design for supporting and sealing the half-shafts in the differential, since the Taylor design is different from the Rockford.

One last recommendation is to use every means possible to find a way to outsource machine work. Many of the top teams do not manufacture their components in-house, allowing them to spend more time on refining their designs, and less time on students attempting to build them. Spending hundreds of hours CNC machining components as a student is an interesting endeavor, especially considering there are only a select few MIT graduates who will find themselves operating a CNC machine after graduation.

The project described here has been a substantial one, performed by a single student over the course of two academic terms. Undertaking a project such as this one is a significant time commitment, requiring countless hours of mechanical design, analysis, and machine time. The driveline package was one of many highly refined designs on the MIT Motorsports MY08 vehicle, which will hopefully be a stepping stone into an era of dominance. The team should look toward the future, building upon their past record of innovation and evolution of designs, and strive to perform at its true potential.

Figure 70: Rear view of MY08 during a testing session

8.0 References

[1] "2008 Formula SAE® Rules"
http://students.sae.org/competitions/formulaseries/rules/rules.pdf

[2] Durand, K. (2005) Design of a Chain Driven Limited Slip Differential and Rear Driveline Package for Formula SAE Applications. Unpublished undergraduate thesis, Massachusetts Institute of Technology.

[3] Scelfo, T. (2006) Lightweight Torsen Style Limited Slip Differential and Rear Driveline Package for Formula SAE. Unpublished undergraduate thesis, Massachusetts Institute of Technology.

[4] James, R. (2004) Design of an Aluminum Differential Housing and Driveline Components for High Performance Applications. Unpublished undergraduate thesis, Massachusetts Institute of Technology.

9.0 Appendix

9.1 Suppliers

Action Bearing Company
201 Brighton Avenue
Boston, MA 02134
617-782-1400
http://www.actionbearing.com/

Admiral Metals
1 Forbes Road
Woburn, MA 01801
(781) 933-8300
http://www.admiralmetals.com/

Aircraft Spruce
452 Dividend Drive
Peachtree City, GA 30269
http://www.aircraftspruce.com/

D.I.D. Racing Chain
http://www.didchain.com

DXP Enterprises
112 North 12th
LaPorte, TX 77571-3125
(281) 471-6241
www.dxpe.com

Keizer Aluminum Wheels, Inc.
3981 Jackson Ave
Orange City, IA 51041
(712) 737-3053
http://www.keizerwheels.com/

McMaster Carr
473 Ridge Rd.
Dayton, NJ 08810-0317
http://www.mcmaster.com/

Patriot Racing Spockets
PO Box 3132
St. Charles, IL 60174
http://www.patriotsprockets.com/

Rebel Gears
392 McKinley Ln.
Crossville, TN 38572
(931) 788-1617
http://www.rebelgears.com/

Rockford Acromatic Products
611 Beacon St.
Loves Park, IL 61111
http://www.rockfordcv.com/

Spectro Oils
993 Federal Rd., Route 7
Brookfield, CT 06804
(800) 243-8645
http://www.spectro-oils.com/

Toyoda-Koki Automotive
2 Jet View Dr.
Rochester, NY 14624
http://www.torsen.com/

9.2 Stock List

Stock	Purpose	Supplier
6061-T6 Plate, 0.75" Thick	Wheel Centers	Admiral Metals
7075-T651 5" Diamter x 24"	Differential Housing, Rear Hubs	Admiral Metals
2024-T351 6" Diamter x 6"	Input Bell, Left and Right Eccentrics	Admiral Metals
4" Diameter Schedule 80 6061-T6 Pipe	Differential Sealing Sleeve	McMaster Carr
7075-T651 12"x12"x0.75"	Differential Brackets	Admiral Metals
1.5"x18"x0.09375 ground prehardened 4142	Thrust Washers	McMaster Carr

9.3 Parts List

Item	Description	Supplier
Bearing, half-shaft	30mm ID, 40mm OD, 20mm width needle bearing	McMaster Carr
Bearing, Left Bracket	NTN 6916LLU	Action Bearing Company
Bearing, Right Bracket	NTN 6010LLU	Action Bearing Company
Differential Gearing	Torsen University Special	Toyoda-Koki Torsen
Drain Plug	1/8 NPT, Aluminum	Aircraft Spruce
Drive Sprocket	12 tooth, 520 pitch, forged steel	Sprocket Specialists
Driven Sprocket	48 tooth, 520 pitch, 7075 aluminum	Patriot Racing Sprockets
Fasteners - Differential Brackets to Engine and Frame	AN8-14A	Aircraft Spruce
Fasteners - Driven Sprocket Bolts	AN4-7A	Aircraft Spruce
Fasteners - Eccentrics to Differential Brackets	10-24 x 1/2" Caphead Bolts	McMaster Carr
Fasteners - Helicoils	5/16 NF x 1/2"	McMaster Carr
Fasteners - Input Bell to Differential Housing	AN5H-7A	Aircraft Spruce
FSAE Axle Kit	Custon Kit for FSAE Applications	Rockford Acromatic Products
Hub Splining	Service	Rockford Acromatic Products
Motorcycle Chain	D.I.D. 520 ERT	Patriot Racing Sprockets
Seal, half-shaft	Chicago Rawhide 11606	DXP Enterprises
Steel Dowel Pins	3/8" x 1.5"	McMaster Carr
Steel Dowel Pins	1/4"x1/2"	McMaster Carr

9.4 Machinery & Special Tooling Lists

9.4.1 Machinery

Equipment	Purpose	Location
Bridgeport EZ-Trak	CNC Milling	Edgerton Student Shop
Computer Controlled Rotary Vice	Differential Carrier Milling	Edgerton Student Shop
HASS CNC Lathe	CNC Turning	Edgerton Student Shop
Horizontal Band Saw	Cutting of Stock to Length	Edgerton Student Shop
Hydraulic Press	Pressing Bearings	MIT Motorsports Shop
Arbor Press	Pressing Steel Pins	Edgerton Student Shop

9.4.2 Special Tooling

Tool	Location Used	Supplier
Helicoil Prewinder, 5/16" NF	Input Bell Mounting	McMaster Carr
Helicoil plug taper tap	Input Bell Mounting	McMaster Carr
Helicoil bottoming tap	Input Bell Mounting	McMaster Carr
Reamer, 0.402"	Journal Pin Reaming	McMaster Carr
1/2" x 2", 4 flute HSS endmill, center cutting	Differential Carrier Element Gear Windows	McMaster Carr

10.0 Acknowledgements

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