Calvin Bolt 3.0: Senior Design Final Report

Team 05

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Engr339/340 Senior Design Project

Calvin College

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Executive Summary

Calvin College's engineering curriculum requires all seniors to complete a capstone project in their last year. The goal of this capstone project is that the seniors bring together everything they have learned while at Calvin and use it to do some good engineering.

Team five chose to improve the previous year's team Bolt project by focusing on two important areas: the steering system and the breaking system. Originally, team five was hoping to improve the Bolt's suspension and breaking system. However, the initial assessment showed that better steering and not better suspension was needed. Team five was able to design a more optimal steering and breaking system. Both systems are reliable and meet their design requirements.

Along with the steering and breaking system, team five also wanted to set up the Calvin Bolt project in such a way that it could be expanded upon by future senior design teams. Team five did this through use of documentation software. Because of this, the next senior design team will have a complete, up to date, and fully functional CAD model to work with.

Team five is hoping that the Calvin Bolt will be used to help bring prospective students to Calvin. Though use of documentation software and improvement of the steering and breaking systems, team five believes the Calvin Bolt is set up for another successful senior design project. Hopefully, the next project will bring the Bolt one step closer to becoming that symbol of Calvin engineering.

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1 Introduction

When a prospective engineering student considers coming to Calvin College, he or she contemplates several factors that come with choosing an undergraduate school. Several of these factors include strong academics, financial aid, and the fun factor of the engineering program itself. Though all of these factors are significant, in comparison to the engineering programs at larger schools such as MSU or MIT, one will ask, "How does Calvin Engineering compare? What exciting things can *I* take part in with engineering at Calvin College? " Team five is hoping to answer those questions with the Calvin Bolt 3.0. You can come to Calvin and leave with a strong education and an unforgettable engineering experience.

The vision of team five is to show that Calvin engineering is not only top notch, but can also be fun and engaging by forming a hands-on learning platform using an electric-powered vehicle. Team five envisions the design of an electric vehicle that not only is functional and cool, but is also designed in a way that allows future senior designs teams to build upon this project over the next five years. Future design possibilities include a solar-powered engine, an A/C system, or perhaps even a redesign of the frame to increase engine efficiency. The hope of team five is that, by using their work done over this year, the next senior design team will be able to take the Calvin Bolt to new levels of complexity.

In addition, team hope that this project will set the bar for future design teams. Engineering at Calvin College needs to be fun as well as exciting. Our hope is that this project will breathe some new excitement into the Calvin engineering department.

The mission of team five is to spark creativity, functionality, and reliability into the redesigning the braking and steering system of the Calvin Bolt.

1.1 Calvin College Engineering

Calvin College Engineering provides a four-year program that culminates student's learning throughout its program by different concentrations. For the first two years, Calvin's engineering courses are designed for students to understand basic concepts from all four fields: mechanical, electrical/computer, civil/environmental, and chemical. After that, engineering students must select one from those options for the remaining two years based on their interest and preference.

1.2 Senior Design Class

Senior Design Project is a year-long course that pursues ultimate learning throughout Calvin Engineering's four-year program. The project consists of two courses, ENGR 339 and ENGR 340, which are required for graduation. In the fall semester, ENGR 339, students are required to form a team to initiate studies on a specific topic, identify encountering challenges, and develop designs including multiple alternatives. ENGR 340, the followed-up design course, focuses on proceeding real manufacturing process based on the final selection from ENGR 339. Lastly, design prototypes require to reflect Christian values and norms to combine with Calvin's engineering curriculum. Therefore, the result of this project is to be successful not only in broadening our perspective of engineering, but also in familiarizing industrial applications from the courses we take.

1.3 Team Members

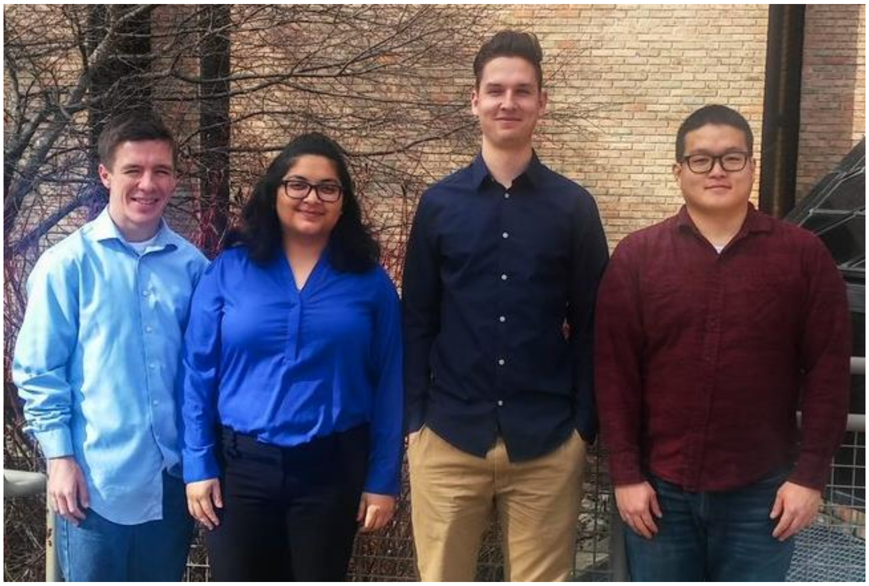

Figure 1. Team picture; from right to left, Dong-sup (Phillip) Kim, Sam Hanover, Bernice Portugal, and Nathan Swaim

1.3.1 Nathan Swaim

Nathan is a senior majoring in physics & mechanical engineering. His hobbies include long distance running and video games. Nathan, upon graduating, will enter the US Army where he will serve as an artillery officer. Future plans for Nathan include, building something really cool and selling it, becoming a missionary in East Africa, as well as breaking 2:40 in the marathon. Nathan's favorite verse is Philippians 4:13 which says "I can do all things through Christ who strengthen me."

1.3.2 Samuel Hanover

Samuel is pursuing a Bachelor's of Science in Engineering with Mechanical concentration at Calvin College. He is from St. Johns, MI. He played four years of varsity soccer for Calvin, other than soccer, he enjoys playing golf and guitar. After college, he will be looking for a full-time job in the mechanical engineering field.

1.3.3 Phillip (Dong-sup) Kim

Phillip is a senior student at Calvin College pursuing a Bachelor's of Science in Engineering. He was born in South Korea and came to the United States for high school and college education. He perceived his talent in mechanical engineering under his father's influence, who is an engineer, and his experience in the Air Force. Phillip's strength is constantly challenging himself to learn new subjects. Along with other engineering experiences, He is currently working as an apprentice for Dr. Tubergen, Calvin College mechanical engineering professor, for the VortX project. After college, he plans to find a full-time job as a professional engineer.

1.3.4 Bernice Portugal

Bernice Portugal is a senior engineering student with a mechanical concentration. After working with a team in high school to design, build, and race a solar-powered canoe throughout Southern California, she was introduced to the world of engineering. Bernice loves discovering unique applications of Engineering, especially in the renewable energy sector. Beyond the classroom setting, Bernice loves exploring new territory, watching films, and, through cooking, learning about diverse cultures around the world. Upon graduation, Bernice will relocate back to her hometown, Los Angeles, California, where she will be able to further explore the vast opportunities Engineering can provide as well as inspire more women to take an interest in Engineering.

1.4 Project Overview

1.4.1 Project Background

The original Calvin Bolt began in 2014 with team four, Volts-Wagon, and has been carried over since. The name, Calvin Bolt, was termed in 2016 with team ten, Calvin Bolt. Both of these previous groups tried to design and manufacture an entire vehicle in less than a year. Although they succeeded in their goal in designing and building a vehicle, their limited time and large goals caused a lack of testing which resulted in components of the vehicle not working properly.

Rather than building an entire new vehicle in less than a year, the goal of team five is to take the first step in a long journey to create a vehicle that truly resembles the Calvin College Engineering Department down to every component. Team five will focus on analyzing and re-designing the braking and steering system to the best of their ability in the time amounted for them leaving the other components to be worked on by future senior design groups. Since this is the first step of many, a version control software will also be used in the process to cover the documentation of the project.

1.4.2 Braking System

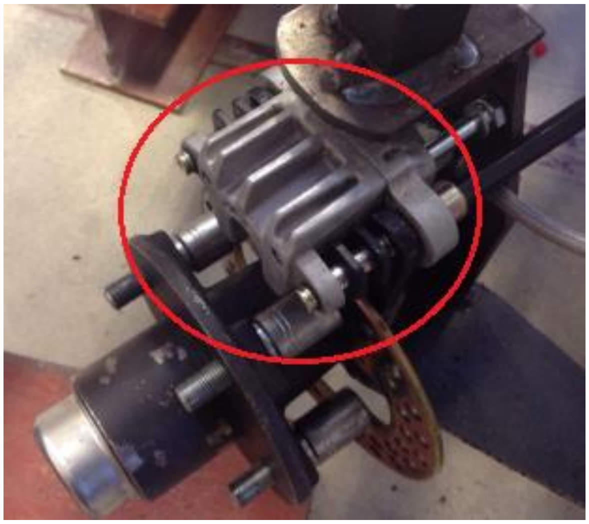

Figure 2. Disk brake of the Calvin Bolt with caliper circled

The braking system of the vehicle was chosen for its inability to function properly. Based on observations from senior design night last year, team ten, along with several professors, stated if any improvements were to be done to the vehicle in the future, the braking system should be one of the first. In their final report, team ten stated that the braking system along with the steering system malfunctioned at the same time on senior design night. However, due to the lack of time, team ten was unable to identify the exact reasoning behind the malfunctions. Therefore, team ten recommended the reasoning for the malfunction was because the original master cylinder did not provide enough force. With the statements mentioned above, along with advice from professors, the braking system was chosen as one of the systems for improvement with an emphasis on increasing the amount of force provided by the master cylinder.

The Calvin Bolt braking system currently consists of two hydraulic front disc brakes as shown in Figure 2, along with no rear brakes. Not only did the previous team, team ten, want to follow the common trend of cars today, by having a front disc braking system over a drum braking system, but also reused parts from the older design team's car, the Volts Wagon, to save money within their budget. As for the reason behind having no rear brakes, members of the previous team, team ten, commented on the issue stating that the mechanism was worn out, having worn out spring/pistons and completely worn out pads; therefore, the mechanism was completely removed. For the scope of this project, focus will only be on the front braking system.

Upon our inspection and test of the current system, it was determined that the Calvin Bolt's braking system did not provide enough braking force to the calipers. To stop the car when desired, the brake pedals are pressure causing the pressure provided from the master cylinder to the disc calipers, by means of the hydraulic fluid, stops the vehicle. Instead, when the brakes are pressed, the vehicle extends its desired stopping distance before coming to a complete stop due to the lack of pressured applied to the calipers.

Figure 3. Parking brake of the Calvin Bolt

In addition, as shown in Figure 3, the parking brake of the vehicle was poorly designed in that the parking brake lever did not effectively lock the braking pedal.

For these reasons, team's goal for the braking system is to re-design the braking mechanism to supply enough force on the calipers, and consequentially the braking pads, without additional stopping distance. A secondary goal, given the circumstances that the main goal is achieved and there is enough time, is to re-designed the parking lever to be suitable for the vehicle.

1.4.3 Steering System

The current steering system is in poor condition. It is difficult to turn and requires some serious strength from the driver to do so. The current steering system transfers the torque of the steering wheel to the wheels through a metal chain around two gears.

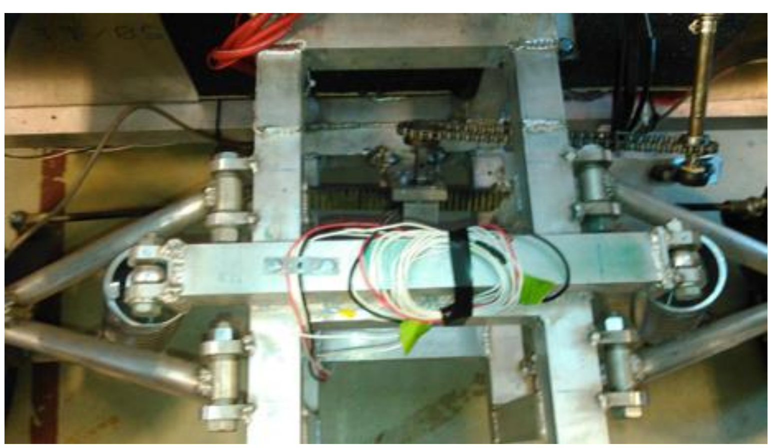

Figure 4. Overhead picture of the old steering system

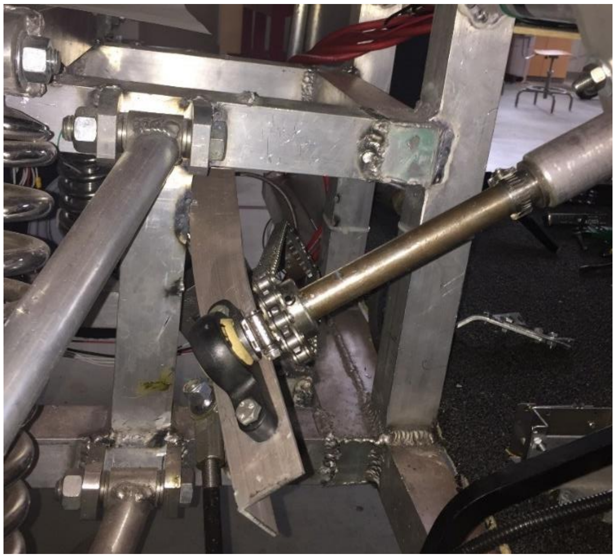

Figure 5. Side view picture of the old steering system

The goal is to design a steering system that is functional and will make it easier for the driver to turn the wheel of the car. As you can see in the Figure 2 above the support beam for the steering shaft is bent, and whenever the wheel is turned it bends even more. This beam is needed because the team before used a gear system to connect the motion of the shaft to the rack and pinion system. Team five is hoping to enhance the gear component of this system for ease of turning as well as more stability for the components that make the system up.

1.4.4 Version Control Software

Working off a previous team's design, such as the Calvin Bolt, can be useful and beneficial given that the current team has the right resources. Along with the slight difficulties in attempting to obtain raw data from last year's design team, team five wanted to create a space that would store all levels of documentation in case future design teams needed them. However, for the goal to become beneficial, the space created needed to be easily accessible, user friendly, and able to manage the multiple changes team five would be making throughout the design process.

This is called version control software. Version control is the management of multiple revisions and redrafting within a project (Thompson); there are several software packages whose sole purpose is version control and others whose package includes version control as an aspect of its purpose. The goal for team five is to use a software where not only can version control take place with CAD files, but where documents of all kind can be stored as well (i.e. emails, Excel sheets, minutes, etc.). The implementation of a version control software will allow team five to provide not only the opportunities, but the right resources for future teams to expand upon their work.

1.5 Motivation

Team five was drawn to this design project because of their passion to learn more about cars and the components that make them up. Team five viewed this project as an opportunity to challenge themselves with a project they were not experts on so that they could learn as they go through its design process. In addition, they themselves hope to see a larger representation of Calvin Engineering on campus in future years.

1.6 Customer

The customer of our design project is the Calvin Engineering Department, specifically, Professor Nielson. The original model for this project had the Student Development Office as its customer. However, due to failure in both functionality and aesthetics from the last two years, the Student Development Office handed it over to the Engineering Department. With the discussion of what to do with the Calvin Bolt, the department decided to keep the vehicle, however had no concrete plans for it. Therefore, as team five spoke with Professor Nielsen about the decision to keep the vehicle, along with its history, they listened to Professor Nielsen's longing for some sort of representation for Calvin Engineering.

1.7 Design Norms

To help students learn Engineering ethics as a Christian and as a student at Calvin College, moral guidelines were constructed in what is also known as design norms. Integrating design norms into their projects during their time at Calvin College, students leave as engineers embodied with a new way of thinking and designing.

Although team five will be incorporate all of the design norms, the team's forefront values for this project are emphasized in the following design norms:

- Trust. As teammates, we need to trust that each one of us is going to weekly put in the required amount of work for this project. This course involves little outside supervision which means teammates must hold each other accountable. Not only do we as teammates need to trust each other, we also need to make sure the next senior design team can trust us as well. This means our calculations will need to be sound regardless of whether or not the professor checks them at the end of the course.
- Integrity. There are no solution manuals in this course. All of our references and pictures need to be cited correctly.
- Stewardship. Using a vehicle from previous groups, team five would like to keep as many parts as possible. In addition, since the time spent on this project is limited and its results will affect future groups, team five must not waste time, but rather use it to the best of their ability.

Our theme verse comes from 2nd Chronicles 22 which writes

"David said "My son Solomon is young and inexperienced, and the house to be built for the Lord should be of great magnificence and the frame and splendor in the sight of all nations. Therefore, I will make preparations for it."

The next few chapters of the book of Chronicles describe David's preparations to build the temple of God. The next few chapters describe the extensive preparations David makes for his son. He recruits masons and craftsmen. He stockpiles large qualities of gold, silver and stone. He also builds a worship team out of a group of Levites. (1st Chronicles 25:1)

David wanted to make sure that God's temple was special. He was also wanted to make sure that God's people were excited and joyful when they came to the temple. To do this, David not only made extensive preparations for the temple construction, he also spent years writing songs (known as the Psalms) which would be sung in the temple courts.

David wanted to make sure God's people were excited and happy when they came to worship. Team five is the same way. It wants to make engineering fun and exciting. By making the Calvin Bolt functional and well documented, team five hopes that the next senior design team will be able to go further than any Calvin Bolt team has gone before.

When Solomon completed his temple, the structure was so amazing that people from all over the world came to see it. David's preparations made a significant impact on the future of Israel. Team five wants to impact the future of Calvin engineering. By making preparations for the next senior design team, team five is hoping that the next senior design project will attract perspective students from all over the world.

2 Requirements

The Calvin Engineering Department decided to keep the vehicle with no concrete plans for its future. Along with team five's passion to learn more about cars, the Calvin Engineering Department allowed the team to carefully inspect defects the car in its current state contains, and requested the team to improve its current design as effective as possible. This led team five to conduct a platform in which every year a team would work on certain systems and aspects of the vehicle to learn and improve upon them. To begin this platform, team five discussed the major issues with the Calvin Bolt which led to the requirement of needing to improve upon the braking and steering systems before anything else. With systems chosen thorough research on the Calvin Bolt prior to the initiation of the project, depending on different systems and components.

2.1 Braking System

As stated in the final report of previous team, the main problem in the braking system, especially for the disc brakes on the front tires, was the lack of adequately amplified force from the master cylinder. However, to confirm the prior group's final conclusion, the entire brake system had to be inspected thoroughly to insure all parts are functional and within specifications; specifications were compared to those of a car rather than a golf cart to increase overall safety. Assembly of the disc brakes concluded to be functional, however, the force to impede rotation of the rotor was concluded to not be enough to cause the vehicle to come to a complete stop when desired.

Team five noticed that to operate the Calvin Bolt, one needs to press the brake pedal multiple times, and all the way down to the floor, for the vehicle to stop somewhat completely. For this reason, the team related the core problem to the efficiency of the master cylinder. Therefore, improvement designs for the braking system would be focused on the amount of force provided by the master cylinder onto the brake pads via the calipers. For a visual understanding of the braking mechanism, see Figure 6 below. In addition, to ensure functionality and reliability, team five was required to replace any components that do not meet a good standing in their own service conditions based on several car repair manuals.

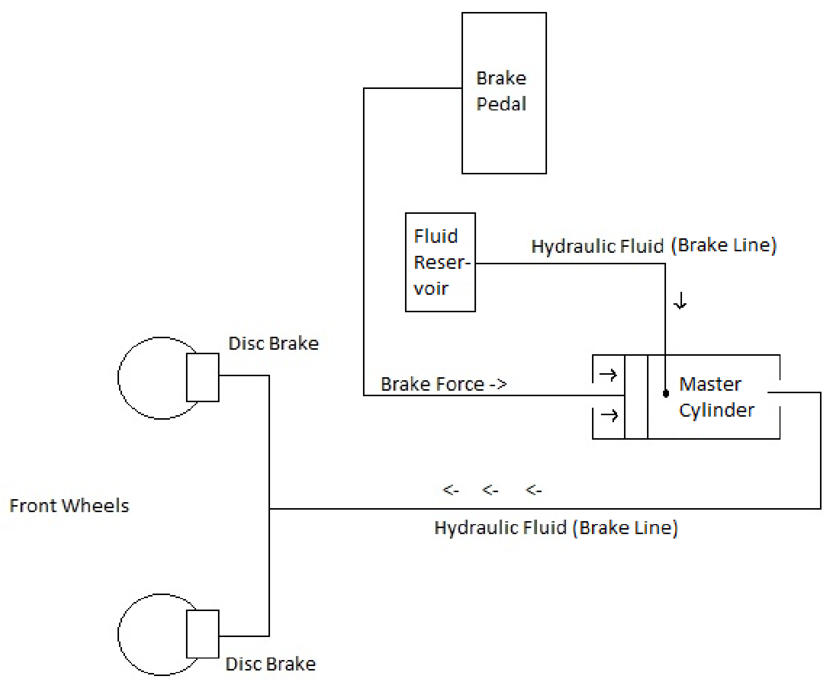

Figure 6. Braking mechanism of the Calvin Bolt

However, on the other side of the project scope, team five was required to keep their approved budget at or below $500. Price estimate on each component of the entire braking mechanism was not fully covered and required additional funding. To limit total expenditure, team five thought that it would be wise not to design with huge changes to the original mechanism. Thus, team five decided to keep the same hydraulic disc braking mechanism, as shown in Figure 6, and to save as many parts as possible from the Calvin Bolt. Then, based on repair manuals and necessary calculations, team five decided which parts in the braking system must be replaced to cause a complete stop directly, satisfying its velocity specification (25 mph max.).

Re-designing the parking brake lever was a miscellaneous requirement for our senior design project; a miscellaneous requirement that was completed given that the main goal is completed first and there is adequate time left. Since the previous team directly imported the brake pedal from a used golf cart, the parking brake that was installed did not lock the brakes efficiently for the Calvin Bolt. For making the parking brake operable, team five considered improved angle of rotation and dimension so that the parking pedal completely lock up the brake pedal at 2 x 2 inch across section as shown in Figure 7. Although the parking brake is functional, the improvements mentioned above are to aid in increasing the overall safety of the vehicle if parked on an incline.

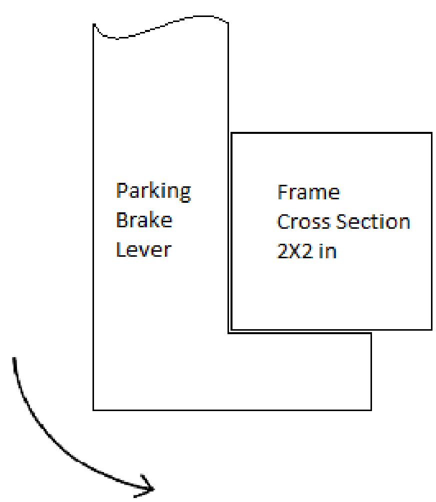

Figure 7. Re-design of the parking brake lever with its own principle.

Thirdly, although it is not necessary for functionality nor reliability, an anti-lock braking system (ABS system) will be implemented to increase safety for the passengers in case of skidding. Team five will be required to design a compatible module by managing only the front brakes of the vehicle to reduce overall cost and simplicity within the design. Research will be required to determine whether or not the ABS module will be combined with the power steering wheel, into the central controller that will potentially be installed, or not. The final decision will be determined in early Spring.

2.2 Steering System

Team five built upon the previous steering system set up by the previous design team. The system needed to be easier to turn while also having an increased turn radius. Design topics considered included Ackermann steering, bump steering, steering gear ratio and toe/camber axis alignment. It was originally discussed that team five would look into getting rid of the chain assembly. However, as the semester continued on, it was decided that team five should optimize rather than remove the current chain gear assembly.

From a controls standpoint, team five originally looked into designing an ECU which would prevent the car from tipping over. Once the power steering system design was ruled out, team five decided not to worry about rollover. See Appendix B for more information on car rollover.

Steering Requirements:
The steering requirements focused on decreasing the force required to turn the wheel, having no slippage in the front wheels (Ackermann steering) and lastly eliminating as much bump steer as much as possible from the steering system setup.

Decreasing the Force to Turn the Wheel:
Team five decreased the force needed to turn the wheel by increasing the steering degree ratio. See section 4.2.9 for more information.

No Slippage in the Back Wheels:
Team five hoped to eliminate slippage in the back wheels by meeting the Ackerman steer condition as closely as possible. See Appendix J for more information.

Bump Steer:
Bump steer would be eliminated or minimized by making changes to the car tie rods or by rearranging the car suspension system.

Avoiding Roll Over:
The power steering system must be designed to prevent roll over. See Appendix B for more information.

2.3 Version Control Software

Version Control software has a high importance for team five in this project. The braking and steering systems team five design will not be of much use to the next group that works on this vehicle if the next group does not know what went into making these components and whether they can be altered to help compensate for the enhancement of another feature or system of the car. Therefore, the systems that team five design may need to be adjusted, but should not take too much time away from the next teams project.

There are several options for implementing version control into the overall project. The first option involves purchasing a license from a company whose software package either comes with a version control aspect or has version control as its entirety. The other option, which is on the lower price end but provides a nostalgic characteristic to the project, is a well-organized flash drive containing all the files, emails, and resources involved in this designing process. The intent of the flash drive will allow students to access the files of previous students whose Calvin account was most likely deleted post-graduation; a problem encountered between team five and the team before. Aside from saving all documents within the design process, the version control aspect team five implements will be required to not only save all CAD files, but track the revisions made to each file as well. An in-depth description of the options can be found in section 4.4.

2.4 Budget

All improvements aimed to meet the $500 budget approved by the Calvin College Engineering Department. Additional funds were considered upon requests and donations, etc. In terms of integrity, the team was upright for any budget for the design as much as possible.

2.5 Project Deliverables

The Calvin Bolt 3.0 team completed a Project Proposal and Feasibility Study (PPFS) and a Final Report. Team five's completion included all drawings, relevant calculations, and the official website.

3 Project Management

3.1 Project Breakdown

Prior to project initiation, the team mapped out noticeable defects of the Calvin Bolt into three major systems: braking, steering, and version control software. The braking and steering wheel system refers to technical issues, which were resulted by poor designing, whereas the version control software refers to the recognized need of establishing combined database for prospective seniors for the future. The breakdown of the technical systems will focus on how team five’s approach to the manufacturing process of prototype.

3.1.1 Braking System

The braking mechanism includes braking pad, disc, calipers (piston and master cylinder), parking brake. The following description indicates how team 5 focused on planning to improve the Calvin Bolt's braking system.

Braking pad – The main friction of the vehicle is created by the contact force between the disc wall and the braking pads. As hydraulic fluid delivers the desired amount of pressure through the pipe, the braking pads begins to clip the brake disc during rotation. As clipping decreases, the speed of the car converting kinetic energy into heat. The pads can also be worn out during that process. For this reason, the right thickness for the pads allow the brake assembly to resist temperature increase and wear. Thus, the condition of brake pad was checked for their capability to withstand wear.

Master Cylinder – Considered the power house of the braking system, the master cylinder sends an amount of pressure via hydraulic fluid to the slave cylinders of the calipers which consequently allow the brake pads to apply a force to the rotor. The amount of pressure (which is then translated to force) that the master cylinder provides, is the biggest determinant of how well the braking system works. Therefore, the focus was primarily set on determining how to increase the amount of pressure.

Disc – The disc (rotor) is the simplest components in the braking system. In braking assembly, the disc is the part where its rotational momentum is used to allow the brake pads to obtain the desired brake force. Wear on the brake disc is caused by the brake pads, and team five needed to inspect its current condition of service. Thickness variation was measured on several different spots on each rotor. Disc's runout was also checked for any damages after test drive. Details, including results, are included in section 4.3.2 and Appendix E.

Caliper – The brake calipers are the device that supports the braking pad that clips the rotor when force is applied. The pistons within the calipers help to transmit hydraulic pressure through the hydraulic lines from the brake pedal. Team five inspected whether the current defect on the braking mechanism is related to caliper pistons (slave cylinder).

Parking Brake – Parking the vehicle is one of the most important functions of the braking system. The parking brake is essential for the braking system because the driver must make sure whether his car is securely locked up to prevent unintended movement. Team five was inspired by the design principle that was already applied to the Calvin Bolt and carefully considered its lever's geometry with the angle rotation of the parking pedal itself.

ABS – The "ABS" abbreviation stands for anti-lock braking system. The system is designed to prevent skidding of a vehicle by preventing the lockup of wheels. In the case where skidding does occur, the system allows drivers to have slightly more control of the direction the vehicle is skidding on compared to the conventional uncontrollable skidding. Thus, to implement this system, an ABS sensor is attached on each of the calipers to redistribute the pressure on the left and right wheels. Although during the Fall, the original plan was to implement both ABS and power steering, it was ultimately determined that neither system could be implemented for reasons described in the later sections.

3.1.2 Steering System

The main time consuming component of this steering system design is the CAD model. This needs to be designed as close as possible to the actual so that we can do proper analysis on its components. It also needs to be altered correctly so that future groups can work off of our design. Team five had to create the whole system in Inventor by scratch because the previous design team only made the parts in CAD for show so they could not be used for analysis. Once this is done we will use it for our analysis as we enhance certain aspects of the steering system that have been specified earlier and will be explained later in this document.

3.1.3 Version Control Software

The progress of the Calvin Bolt will be documented using a version control software. Incorporating a version control software will allow team five to practice due diligence in way similar to modern day corporations (Yeates). Through the version control software, emails, CAD drawings, changes to documents and every aspect of the designing process will be managed through the use the version control software.

3.2 Gantt Chart

Schedule and deadlines for the spring semester are enclosed in Appendix C.

3.3 Team Roles and Responsibilities

Phillip Kim took the lead on fixing the brakes in the Calvin Bolt. He spent a great deal of time going through the theoretical portion of the design by ensuring his calculations and values were correct. He was also the team's webmaster in making sure the website was routinely updated. As for the implementation of the brake system changes, Phillip performed the welding portions needed for the braking system.

Nathan originally put together the team schedule and helped make sure the team was making its deadlines. As second semester moved along, Nathan shifted his responsibility to working with Vault as well as the steering analysis. Nathan also helped with much of the machining done on the Calvin Bolt and other various tasks.

Sam took the lead role on the CAD aspects regarding the steering system. As the Spring semester progressed, Sam shifted his focus to designing the steering system by applying the design changes from the CAD to implementing them practically onto the Calvin Bolt. Sam also did the last set of presentations at the end of the semester.

Bernice took the lead on documentation software during the fall. In addition, she also took the lead role on gathering test data for the braking systems through a series of test. As the Spring semester continued, Bernice shifted her focus to implementing practical changes and testing to the braking system. Bernice also did the last set of presentations at the end of the semester. Her efforts on the breaking system were significant in making sure the Bolt was ready for senior design night.

4 Design Analysis

4.1 Initial Analysis

The initial diagnostics of the car and based off what professors who helped the previous team said, it was shown that the end results of the Calvin Bolt fell short in many ways compared to what the customer wanted from the project. Although there were many aspects of the vehicle that could have been improved, team five decided the wise approach would be to choose the systems that had the largest current impact on the vehicle and improve upon them. They could have worked on multiple systems, however, learning from the past, they did not want to bite off more than they could chew. Therefore, team five decided to focus on one or two systems, and design them very well and documenting their process and results so that future groups could work on other aspects of the vehicle to eventually come out with a car that is well design down to every component.

4.2 Steering System

4.2.1 Research

Based on current research, an electronic power steering system would have been the best design option. Electronic power steering involves no fluids and does not require a running engine to function. It is also easily modifiable with a control system which would have made it an excellent design option for making adjustments.

The electronic power steering system would have required a control system to be designed. The control system would need to be able assist the driver in the torque required to turn the tires. This force will change depending on the speed of the car. When the car is traveling at a high velocity it will assist less than when it is traveling at a slow one. Team five found that the type of control system to use for such an operation a PID (proportional–integral–derivative) controller that uses the angle of the tires as well as the speed, and force that the driver is exerting as in input to then output an added assisting force on the steering shaft. This assistance is needed because of the weight of the car and since there will be future teams working on this car, the weight my change. This is an advantage of using the electric power assisted steering system because the control system will be able to be easily adjusted on the amount of torque that it will assist to the driver.

Below in Table 1 that shows the effect that the PID controller has on the output as the parameters are independently increased. You can see the visual effect of as these parameters are increased in Figure 8 as well.

Table 1. The effect of increasing one of the parameters independently

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability[14]
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_d	Minor change	Decrease	Decrease	No effect in theory	Improve if K_d small

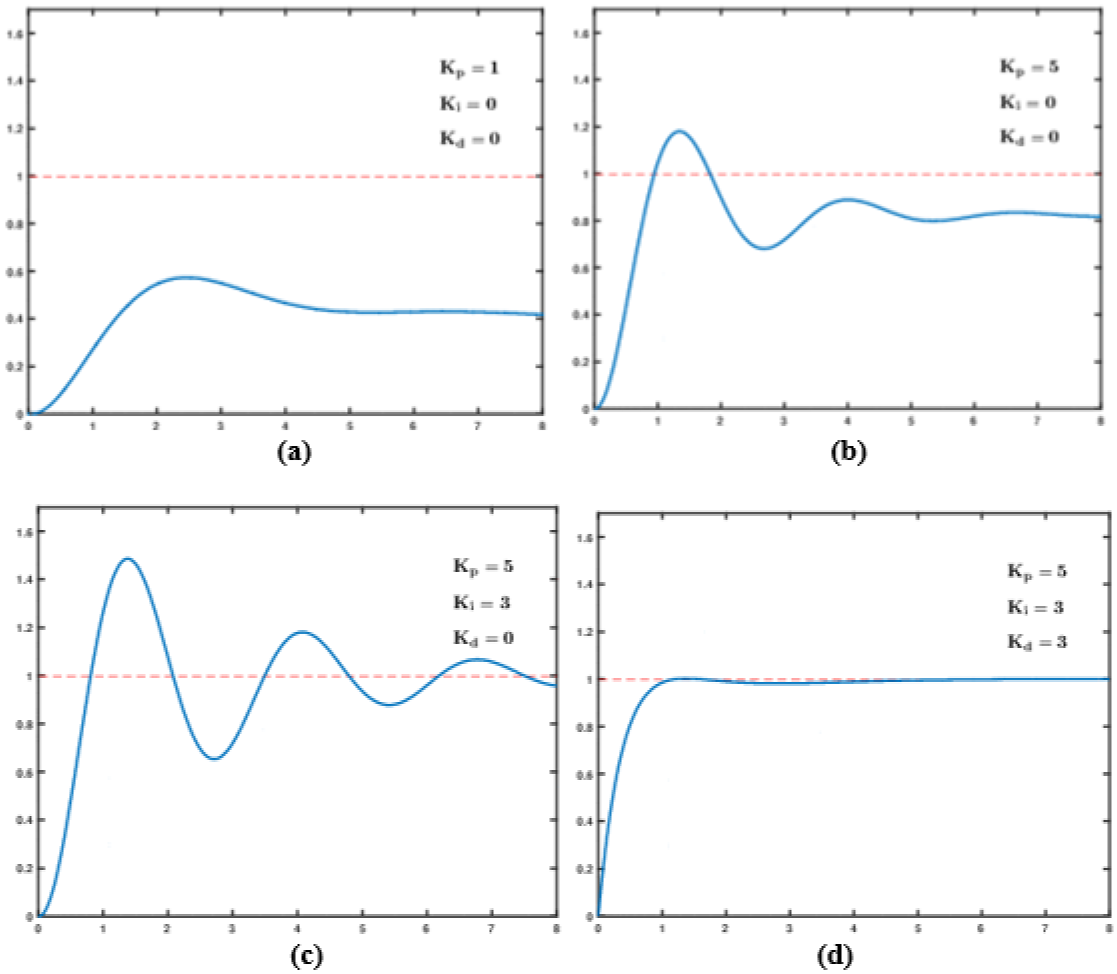

Figure 8. Step response plots with time (sec) on the x-axis and amplitude on the y-axis showing the effect of a PID controller when, (a) No parameters are added, (b) the P parameter is amplified, (c) the I parameter is added and amplified, and (d) the D parameter.

4.2.2 Alternatives

The two main alternatives to power assisted steering were hydraulic power steering (HPS) and rack & pinion.

Rack-and-pinion was the current design and required a large amount of force to turn the wheel. An alternative here is to modify the current rack and pinion system by removing the chain and attaching the shaft directly to the rack which shifts the wheels. It was ruled that such a design would not have worked due to the nature of the current frame. This could not be done without lengthening the rack or changing the location of the steering wheel.

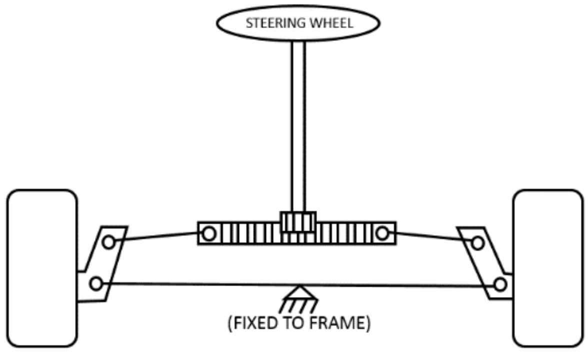

Figure 9. Simple rack-and-pinion steering system

The hydraulic system does not require an AC motor. However it would have required a compressor which would have required a motor to use it. Thus, the hydraulic system was ruled out. Had it been feasible, an electronic power steering system would have been optimal.

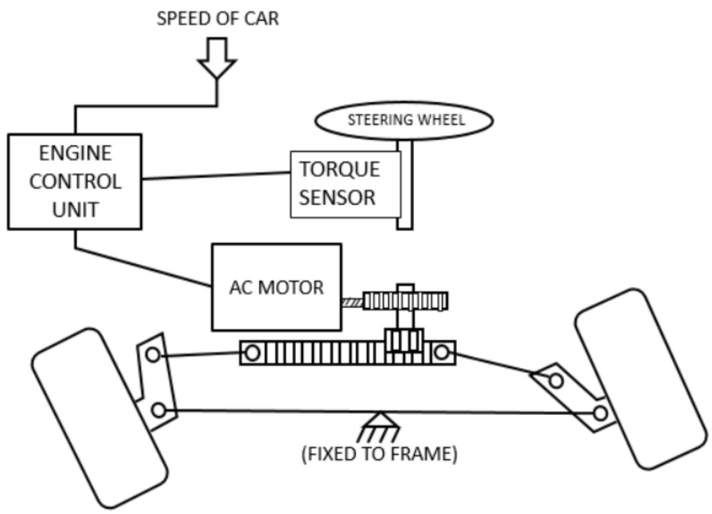

Figure 10. Diagram of a joystick configuration of an electronic power assisted steering system.

4.2.3 Decisions

In the end while considering all of the alternatives based on efficiency, cost, and variability, team five decided to enhance the rack and pinion system that was set in place. This was the best design for both functionality and variability. An electric power steering system was ruled since there was no electrical engineer on the senior design team.

4.2.4 Implementation

Team five had sufficient information to implement a modified rack and pinion steering system. Much of the first half of second semester was spent on the design. The second half of second semester was where most of the analysis on the project took place.

4.2.5 CAD Model Construction

A fully functional CAD model of the car was created. Special care was taken to make sure the CAD model was a geometric replica of the current Bolt. Tolerances were assigned based on functions. Special fits were measured to the thousandth of an inch and all other components were measured to at least the hundredth of an inch.

The steering section of the CAD model is shown below in figure 11.

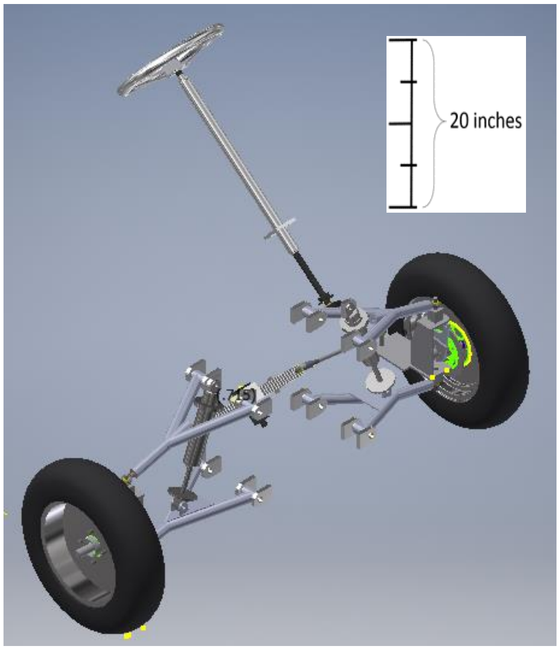

Figure 11. Cad model used to test the Ackerman conditionCondition-The real assembly2.iam

See Appendix L for images of the original gear & chain assembly.

4.2.6 CAD Steering Analysis-Initial Assessment

Once the CAD model was assembled, testing of the geometry could begin in order to assess what changes needed to be made in order to make the steering system more effective. The Calvin Bolt steering assembly was tested in Autodesk inventor to determine what geometric changes needed to be made in the new design.

4.2.7 Ackerman Steer Analysis

Ackerman steering is a geometric constraint which allows the car to turn without slippage occurring between the wheels and the road. For more information on Ackerman Steering, see Appendix J.

Using Inventor's drawing tools, the CAD model was then tested to see if the current setup met the Ackerman condition. The plots for the initial test are shown below.

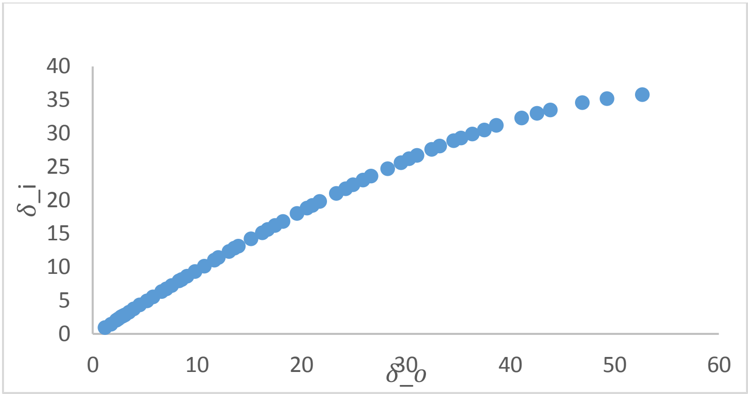

Figure 12. Left turn testTurn Ackerman Steer

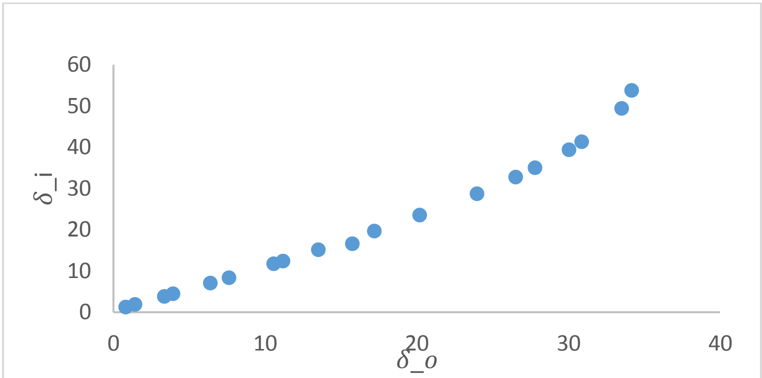

Figure 13. Right turn test Ackerman Steer

It should be noted that the right turn has a larger turn radius than the left wheel because the physical structure of the front part of the car is keeping it from turning as sharply. For information on the correct geometry needed to achieve the Ackerman steering condition, see Appendix J.

Figure 14 below shows the apparatus that was used to test the Ackerman condition.

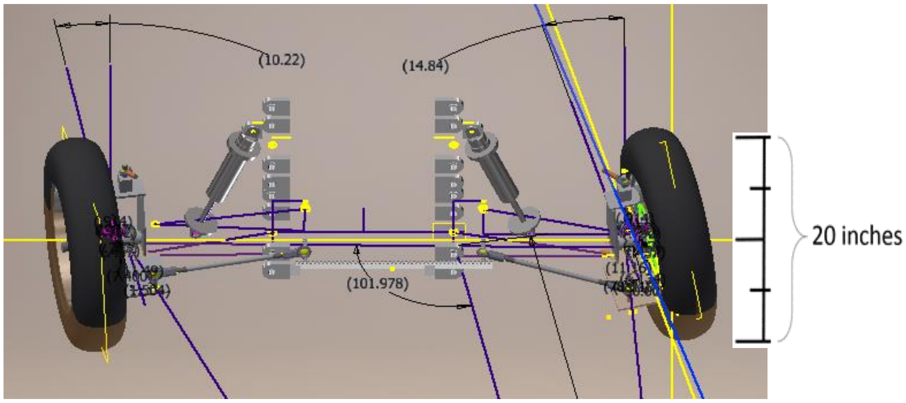

Figure 14. Steering apparatus (-The real assembly2.iam)

The initial setup showed that the original steering setup did not meet the Ackerman condition exactly but as team five attempted to alter the system to make this ratio closer team five found that the change would be so small that it could end up going further away from Ackermann steering. The result of this analysis is shown below in Figure 15.

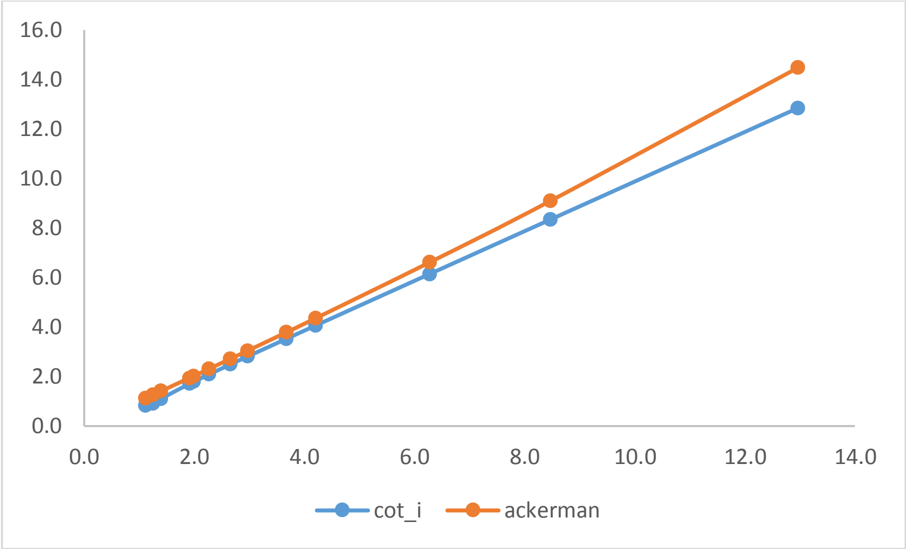

Figure 15. Calvin Bolt steering system compared to Ackermann steering

Using this information, the geometry of the CAD model was corrected by using CAD software features. Autodesk allowed for the construction of lines which where both parallel and perpendicular to one another. It also allowed the user to define angles between these axes which allowed the user to measure these relationships. An example of this can be found in figure 16 below.

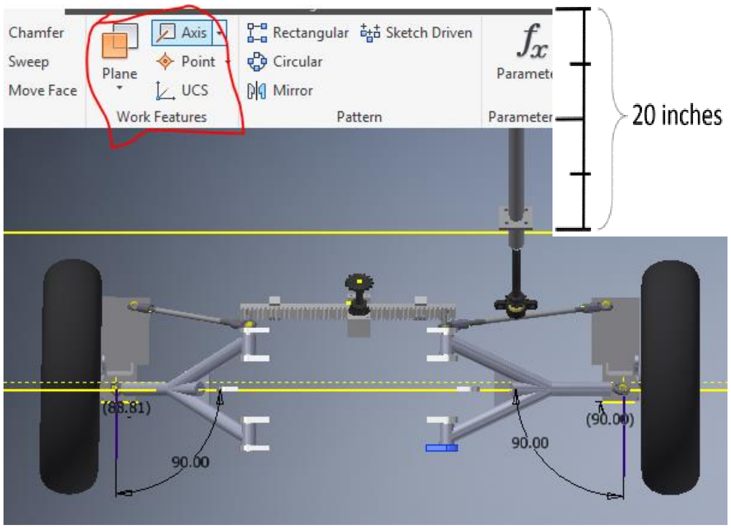

Figure 16. Example of using the CAD software to measure relationships such as toe angle. The real assembly2.iam

4.2.8 Bump Steer Analysis

A bump steer analysis was also done on the car in order to determine the correct length of the tie rods. Using the cad model, the team was able to vary the length of the tie rods in order to determine how to best minimize the bump steer. For more information on bump steer, see appendix O.

The left wheel bump steer varied by **0.46º per inch** while the right wheel bump steer varied by the same amount. The results are shown below.

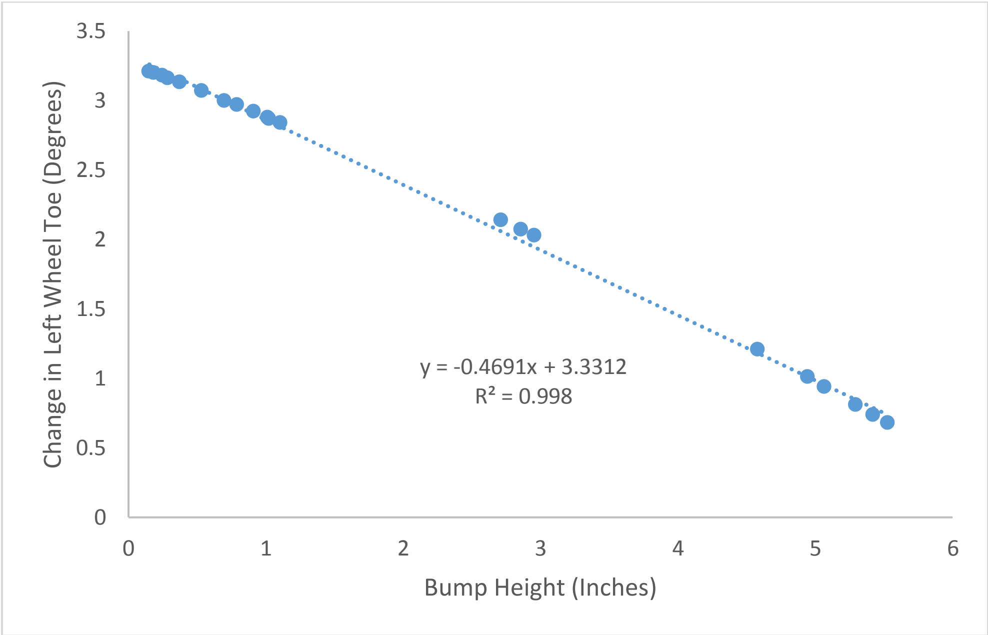

Figure 17. Bump steer of left wheel before modification

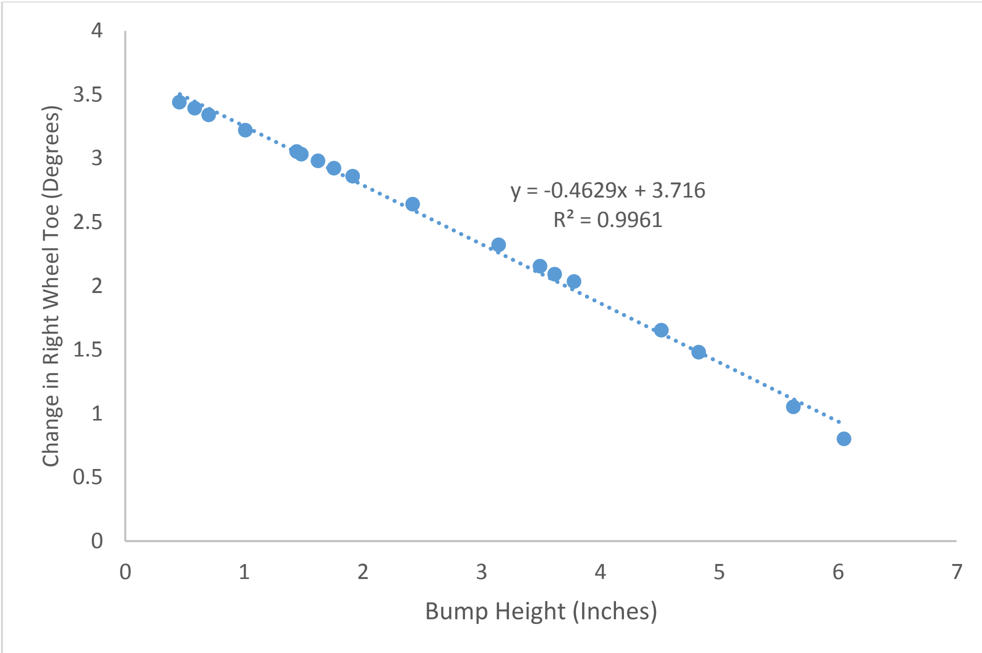

Figure 18. Bump steer of right wheel before modification

Having made the necessary changes to the tie rods, the bump steer was again validated using the constrained CAD model. The results were the following:

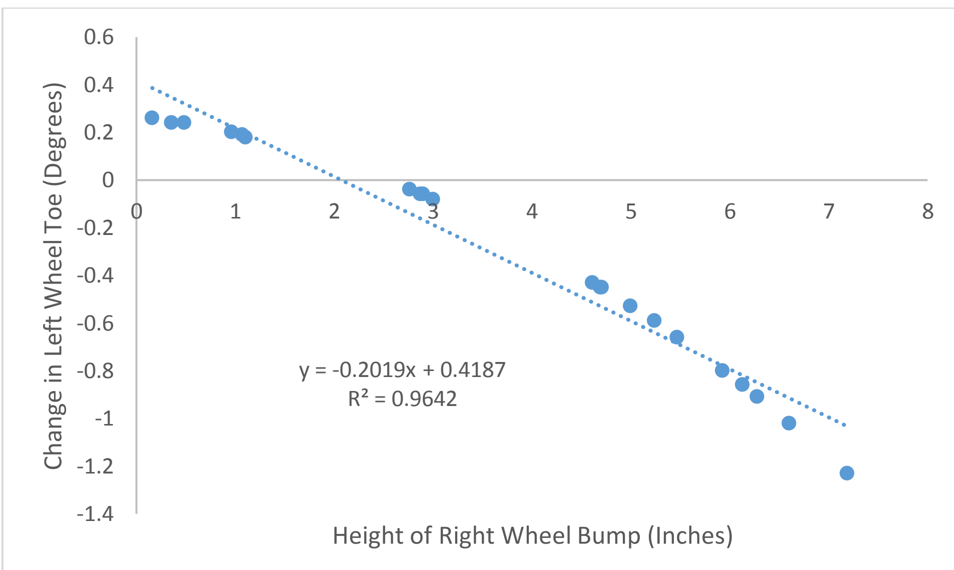

Figure 19. Bump steer of left wheel after modification

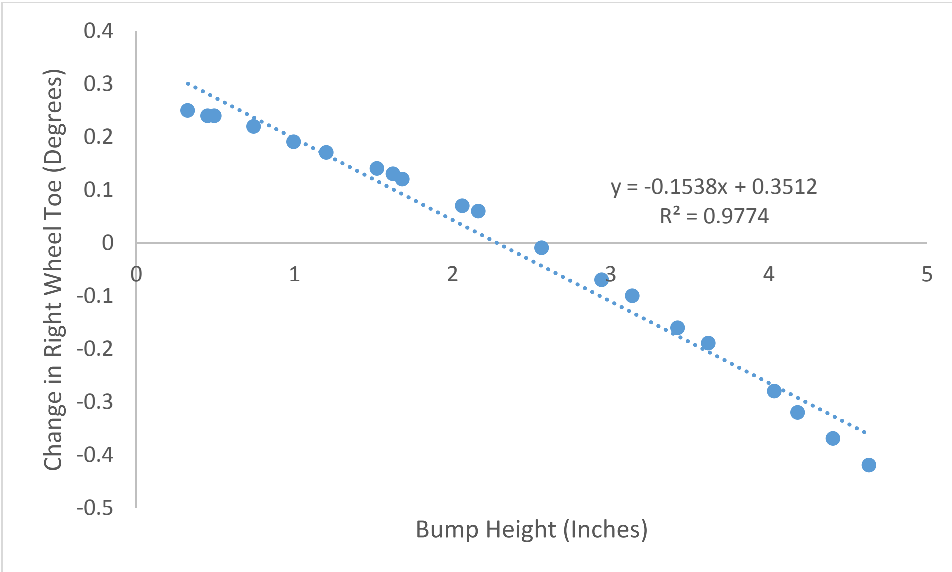

Figure 20. Bump steer of right wheel after modification

The left wheel's bump steer improved to **0.20º per inch** while the right wheel's bump steer improved to **0.15º per inch**.

The bump steer could not be eliminated completely from the Calvin Bolt. This is because the setup of the current suspension system prevents achievement of zero bump steer. Zero bump steer would require redesigning the suspension apparatus. For more information on achieving zero bump steer, see appendix O.

4.2.9 Steering Degree Ratio

The steering degree ratio is the ratio of the change in degree of the steering wheel to the change in degree of the wheels on the ground. Team five used the CAD model that they designed to measure this phenomenon for multiple angles throughout the turning span to get a ratio for the previous steering system which came out to be an 11:1 ratio. This means for every 11 degrees the steering wheel is turned, 1 degree of the tires are turned. The standard steering degree ratio for commercial cars is from 12:1 to 20:1 and so the current system falls short. This one degree difference may not seem like much but since our system is not power assisted it will be harder to turn than commercial vehicles. When this ratio increases it also increases the ease of torque required form the user on the steering wheel. Therefore, we decided to shoot for a ratio of 25:1 so that we could compensate for the lack of power steering but not use a ratio so high that you need to turn the wheel a ton of times just to turn the wheels a little bit.

To obtain this ratio team five looked to alter the ratio of the gear on the steering shaft to the gear in the shaft that connects to the rack, both of which are pointed out in the Figure below. The current system had a ratio of 1.33 and needs to be increased to increase the steering degree ratio. Below is a graph for how altering the gear ratio alters the steering degree ratio and the raw data that obtained this graph is shown in Appendix M.

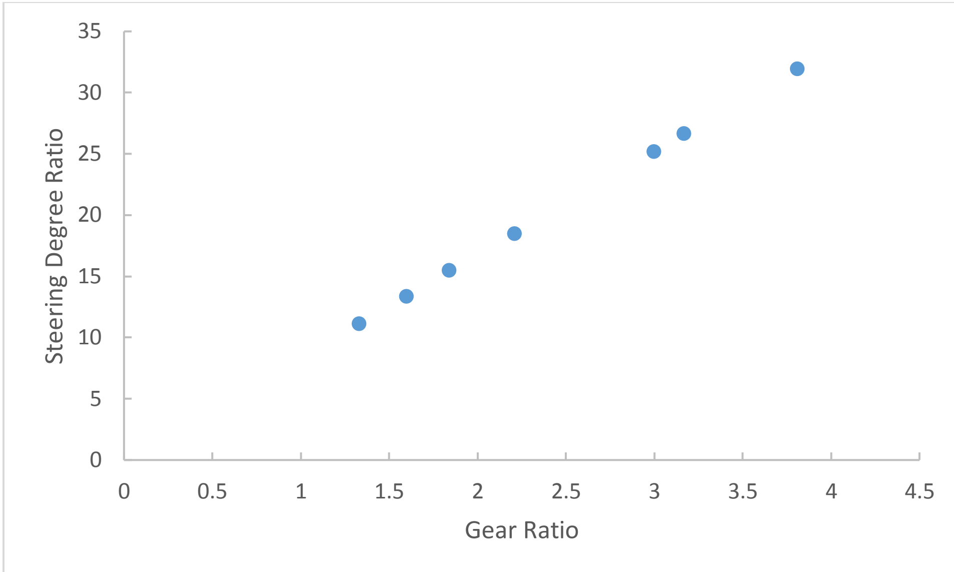

Figure 21. Effect on steering degree ratio from the gear ratio

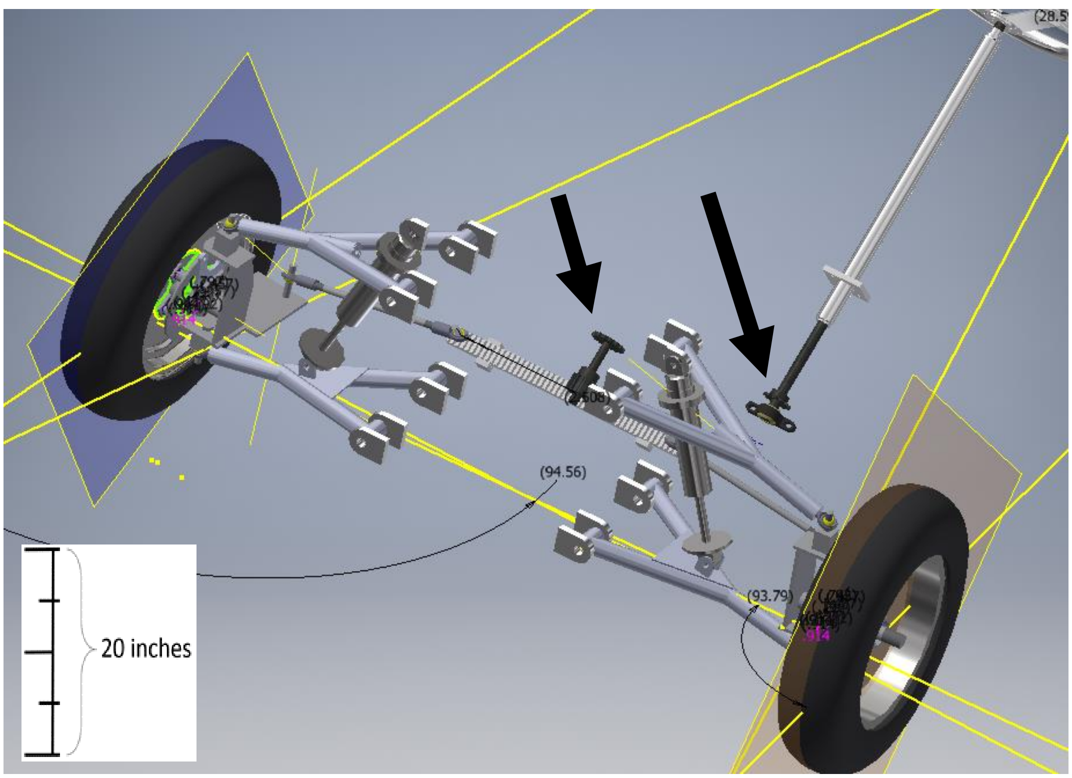

Figure 22. Gears altered to change the gear ratio to obtain the steering degree ratio-The real assembly2.iam

4.2.10 Shaft Supports

One of the problems that was a pointed out by the last team was the supports for the shafts in the system. The steering shaft was one of the components that broke down during the test drive because it popped out of the bearing that supported it. To fix this team five tapped the end of the shaft so that they could use a bolt and washer to cap the other side of the bearing as shown in Figure 23 below. For the angle iron shown in this picture team five also added a support that attached down to the frame because it would bend when the steering was activated and with the smaller gear that was added it would only be put under more force.

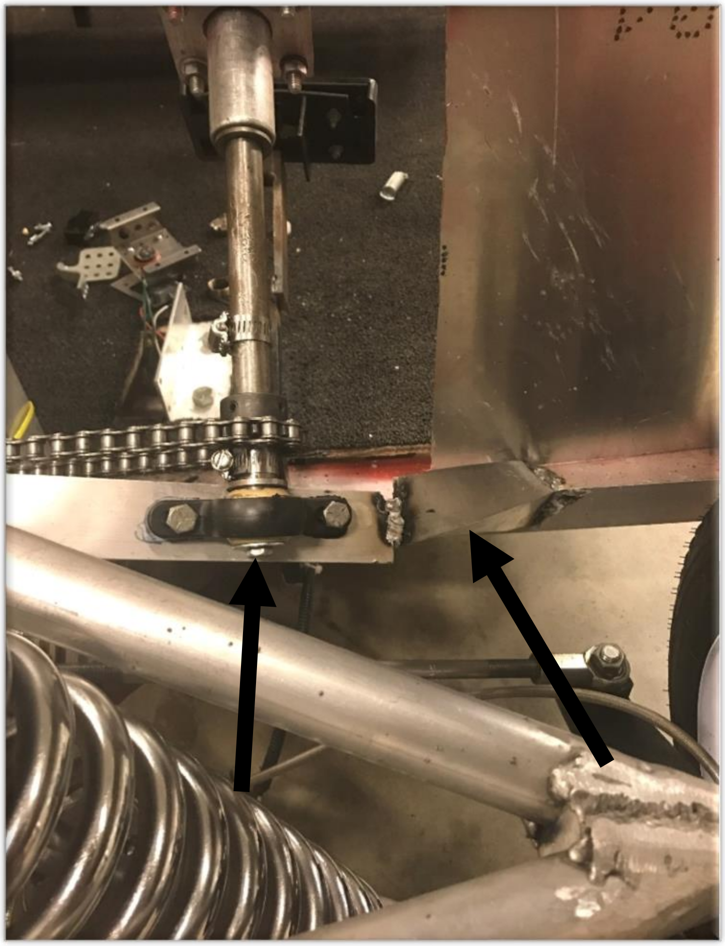

Figure 23. Steering shaft cap and support

The shaft that was connected to the rack and pinion system was another issue since it was only supported by a steel block on the end that went around the rack as shown in Figure 24. The Aluminum block was originally not in the system so the rod was only supported by the steel block on one side and slightly by the rack. The aluminum block allowed the shaft to be supported on both ends of the shaft for increased stability.

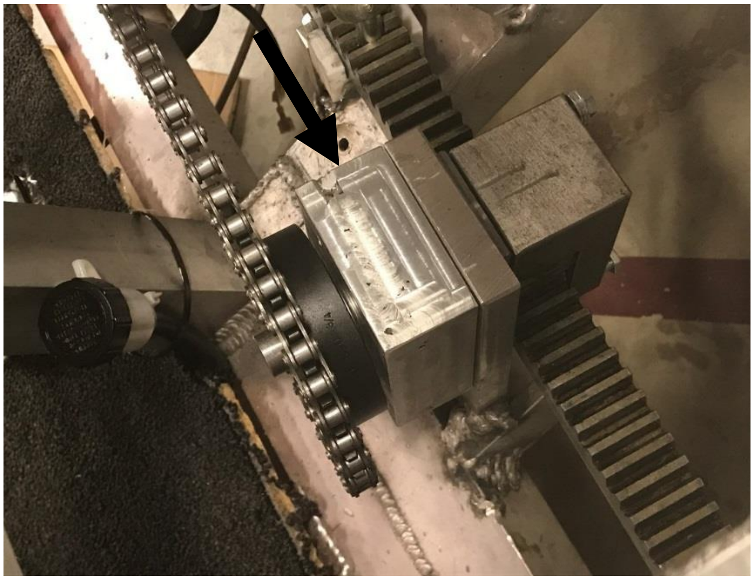

Figure 24. Added support for shaft that connects to rack

In Figure 25 and 26 below you can see that team five altered the supports on the rack. This was necessary because when the steering system was engaged the rack would go up and down off of those original supports creating a large amount of slop in the system. To get rid of this slop team five welded those supports further in on the frame so that the rack would never leave that surface throughout the turning radius, and pressed them up tight against the rack so that there was no clearance between the rack and support on either side.

Figure 25. Rack support replacement for left side of the steering system

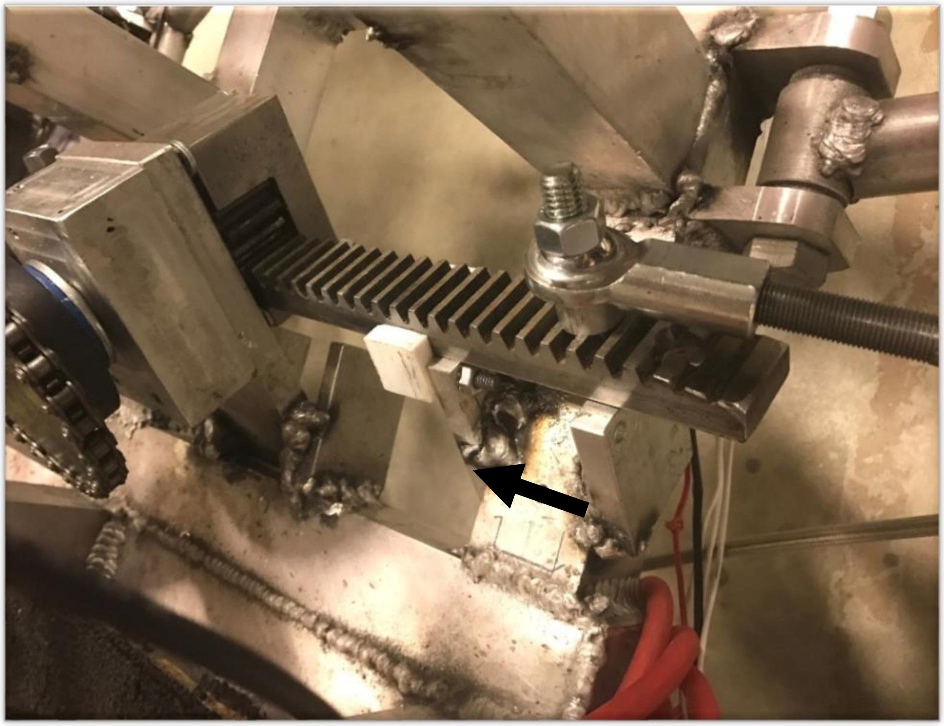

Figure 26. Rack support replacement for right side of the steering system

Figure 27 below shows the FEA analysis for the shaft that connects to the rack as it was originally supported. The gears and other aspects that don’t effect the analysis are suppressed so you can see where the shaft was supported and the stress that it went under. For the original system the max amount of stress in the shaft came out to be 6.027 ksi. Figure 28 shows the same shaft but with the added support that team five implemented so that the shaft was not only supported on one end. As you can see this support decreased the maximum amount of stress in the shaft lowered to 2.055 ksi. Therefore, the support that was put in place decrease the stress in the shaft by about 66%.

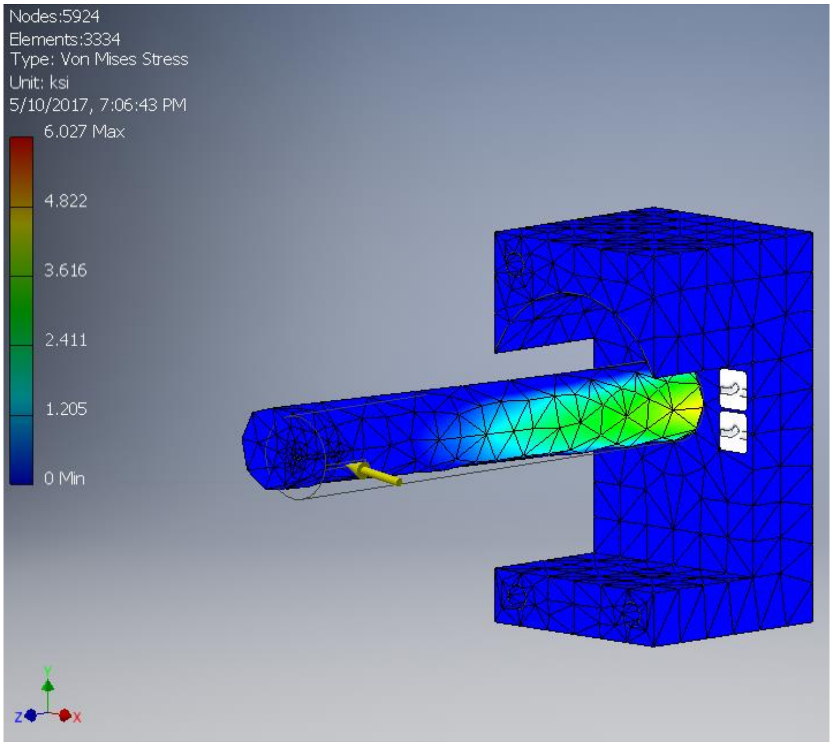

Figure 27. FEA on original shaft that connects to the rack (Figure 24)

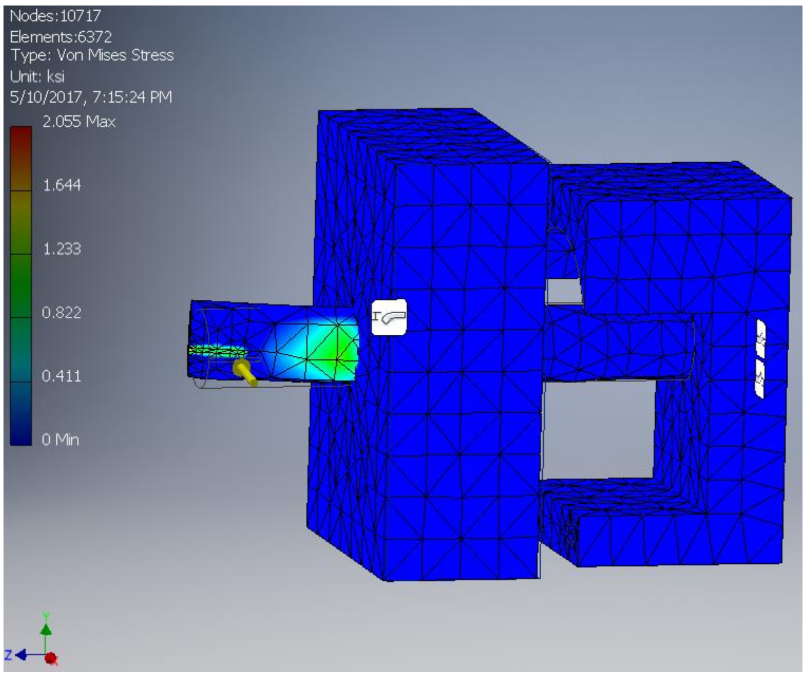

Figure 28. FEA on shaft that connects to the rack with added aluminum block support (Figure 24)

4.2.11 Toe & Camber Axes

Toe Axes

The car’s front wheels were also realigned. The toe axes were set so that the front wheels at the neutral position were parallel to each other. This was done by attaching two straight metal rods to the outside wheels while the steering system was fixed in the center position. One foot markings where then measured out on these segments. The steering system was then adjusted until the distances on these lines were the same. See figure 20 for a display of the setup.

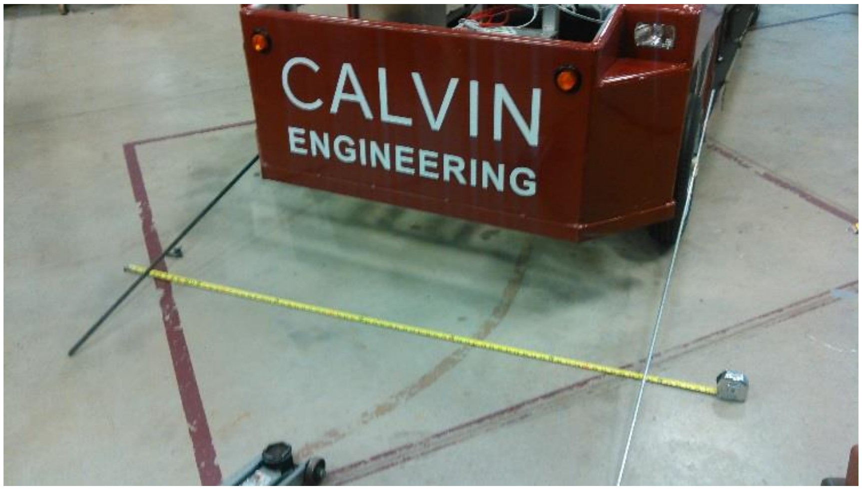

Figure 29. Camber alignment of the front wheels

Camber Axes

The camber axes were aligned such that the tires were perpendicular the ground. This was done using a machine shop level. The level was placed on the wheel and the suspension joints were adjusted accordingly.

Figure 30. Camber axis alignment

4.3 Braking System

Last fall, team five inspected every item involved in the braking assembly for two main reasons. The first, to understand the braking system and how it functions. The second, to then understand and search for the cause for why the braking system malfunctioned. The suggestions were focused on modifying the original parts of braking mechanism in terms of functionality. Then, a mathematic model was established to understand theoretical as well as mechanical aspect of braking system to point out what causes inadequate hydraulic pressure on the brake pads.

4.3.1 Specification Defined

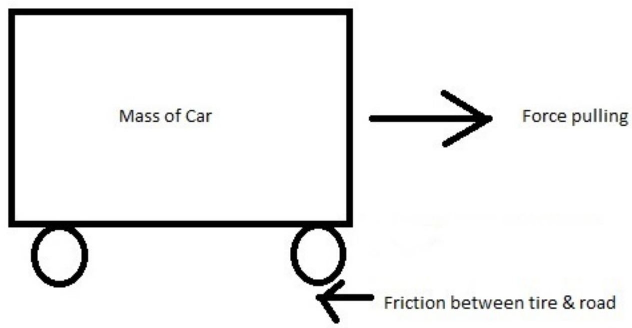

Figure 31. Schematic diagram of static test.

To establish how much braking force is required to stop the car, the amount of force required to move the car when the wheels are locked up is required. Due to the space and time constraint for performing the experiment, team five understood the advantages of having static test on the Calvin Bolt. In addition, having a static test within the engineering building would allow team five to maintain a consist environment for their testing as well as be able to meet their goal on asphalt if it is met with smooth concrete first. As shown in Figure 31, static tests were performed to see how hard it is to pull the car when brakes are applied; the brake force is considered as internal friction.

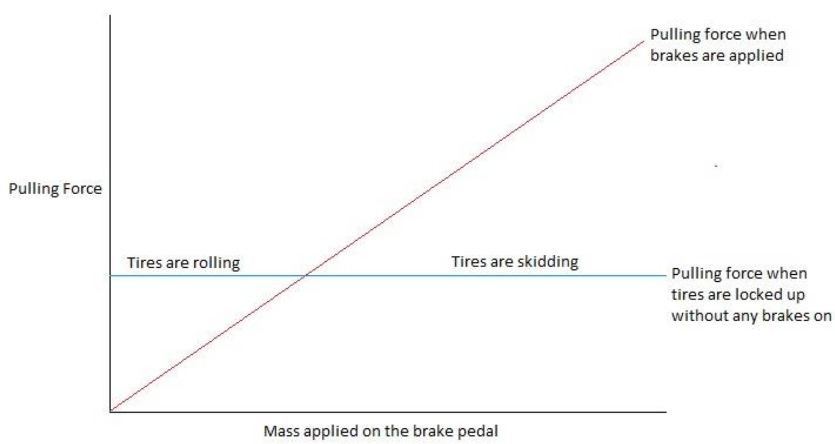

Figure 32. Schematic scenario for brake test

The general idea of diagnosing the brake system is based on a relationship between the pulling force and force applied on the brake pedal. Once the amount of force it takes to not only lock up the wheels, but have the car slid across the concrete, is determined, the force applied on the brake pedal becomes the only decision variable in braking system. Team five expected the tires of the Calvin bolt to skid, especially when it exceeds the blue line in Figure 32.

In addition to the testing procedure and as mentioned earlier, team five preferred to establish our base case on a dry concrete flooring in the engineering building, where the friction coefficient is nearly less than half the outside coefficient, 0.7. The reasoning for this is because we wanted to understand the dynamics of the car under a controlled environment regardless of road conditions and weather. Measurements were recorded in English units: lbf, lbm, and inch. For the base case, team five applied roughly 40 to 45 pounds of mass on the brake pedal according to *the human factors design handbook* by Wesley Woodson (ISBN: 0070717680); 70 pounds were also applied to measure data when the pedal is pressed further.

Based on the results of our initial test of the Calvin Bolt (both physically and theoretically), team five realized that the car would require around 300 lbf to slide on dry concrete (with four passengers aboard); See Appendix Q for estimated pulling forces. Thus, the design goal, for the braking system, is to provide a lock up (on the wheels) with a braking force of 300 lbf or more on a smooth concrete ground with a coefficient of friction of 0.3. Team five has made the assumption, that if the vehicle is able to lock up at 300 lbf on the smooth concrete ground, the vehicle will be able to stop on a ground with a much higher coefficient of friction.

4.3.2 Design modification

Braking pad - In the original PPFS, team five mentioned the need of replacing brake pads. However, according to Jake’s lift kits, the manufacturer of old disc brake kit, the thickness of brake pads with 0.14 inch are considered to be new; a measurement the current brake pads fits into. Team five also figured out that changing the size of the brake pads would require a change of the caliper. This would eventually require team five to re-design the wheel bracket to fit the new calipers on both the right and left wheels. Due to the budget constraints, the complexity, and time provided, team five decided to keep the same brake pads.

Disc – In terms of general thickness and thickness variation according to inspection manuals, the disc provides enough thickness and thickness variation. Thus, the brake rotor does not need to be replaced. See Appendix E for rotor inspection results.

Figure 33. Brake caliper used

Caliper – Team five initially planned to change the slave cylinder with an increased amount of the number of pistons (two piston system), though with smaller diameters. However, team five decided to keep the same type as shown in Figure 33 because of the time constraint for the overall project as well as the complexity of the project in redesigning the wheel brackets as mentioned earlier. Since team five wanted to stay within the project funding, less than $500, parts that strongly contributed to the braking functionality were bought and replaced while others were dismissed. The piston diameter of current caliper is one inch.

Figure 34. Fluid leak in red circle (left) and damaged bleeding screw (right)

During static testing with the Calvin Bolt, when the brakes were applied, team five found leakage of brake fluids from both sides of calipers which can be seen in Figure 34. One of side had a more severe leakage than the other due to the thread damage in its bleeding screws. The thread damage caused distortion while the brake force was examined which led to its replacement. The replacement was the same model (part number: 7240).

Figure 35. Image of a crashed washer

Washers that act as gaskets on the inlets of the slave cylinders were also replaced for preventing potential leak in further tests. Team five noticed that the gaskets on the inlets should not be re-used once they are crashed inward as shown in Figure 35.

Master Cylinder – After the completion of several test and theoretical calculations, team five concluded that the original master cylinder had a good bore diameter of 0.5 inch. The master cylinder should have provided a strong pressure in the brake hose with the maximum of 1100 psi. However, team five still confirmed the lack of clamping force between the pad to the brake disc since the front tires kept rolling even though the brakes were applied. Thus, team five realized that the stoke of original master cylinder, approximately 5/8 inch, was not long enough to pump fluids to calipers at a time. For this reason, team five decided to install a new master cylinder with a longer stroke.

Figure 36. The new installed tandem master cylinder

As shown in Figure 36, the new master cylinder has twice the stoke (1.3 inches) with slightly bigger bore diameter (5/8 inch). Team five considered a tandem piston better than a single piston for the future design groups who plan to implement the rear braking system of the vehicle. Team five expected that changing the dimension of brake lever arm would compensate potential pressure loss by selecting a master cylinder with larger piston diameter. More information on the new master cylinder can be found at Willwood.com (part number: 260-11097).

Parking Brake – Based on the CAD drawing, team five decided to modify the original shape of parking brake. Given a limited budget, team five decided to fully utilize the availability of the metal shop for materials. Aluminum (6061) and Steel (1008 or 1010) were the two options for the new design of the parking brake. Since the team must ensure complete lock-up, the geometry of the current level was reconsidered and changed to take into account the rotation of the lever itself. The rotation of the lever was considered how far the brake pad would slide on the edge of the car frame in which its lengths are 2 by 2 inches. Having the new design, team five welded all parts to form the new design of the parking lever. New assembly of the design with its CAD model is as shown below in Figure 37.

Figure 37. CAD screen shot (left) and real implementation of parking pedal (right)

Price per unit was not considered due to the metal shop's availability. As for the material options of steel and aluminum, the tensile strength of each material became the focal point in the final design than any other aspects since team five mainly focused on safety factor for damage on the lever. Due to its higher tensile strength, steel alloy was chosen over aluminum; See Appendix G for material properties for steel and aluminum. Dimensions for new parking pedal lever is enclosed in Appendix S.

4.3.3 Mathematic Approach: Braking Lever

$$Moment = Force * distance\ to\ pivot$$

Equation 1

Besides replacing parts for full functionality of the brake system, team five considered another improvement that can be achieved to reach the goal. As mentioned above, team needed to know how much the brake lever arm should change so that the moment around the pivot can be increased. Based on a simple schematic diagram as shown in Figure 38, team five applied the simple moment equation shown above.

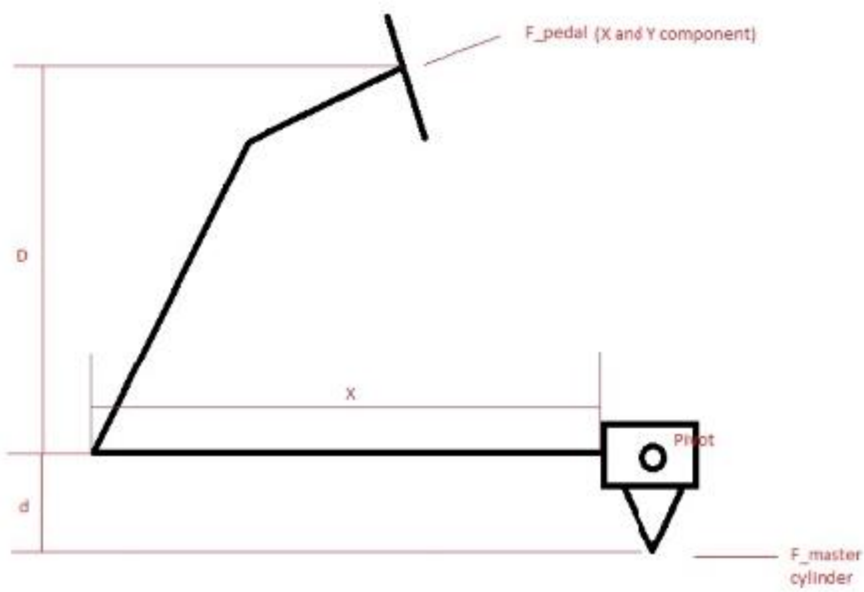

Figure 38. Simple schematic of brake lever arm

$$\frac{F_{MC}}{A_{MC}} = \frac{F_{SC}}{A_{SC}}$$

Equation 2

To relate the force applied on the brake pad to the brake disc, Pascal's law was used. In regards to the formula above, 'MC' and 'SC' stand for master cylinder and slave cylinder (the caliper) respectively. For further calculation to the pulling force of the car, another simple schematic was used to connect relationship with the force applied on front tires as shown in Figure 39.

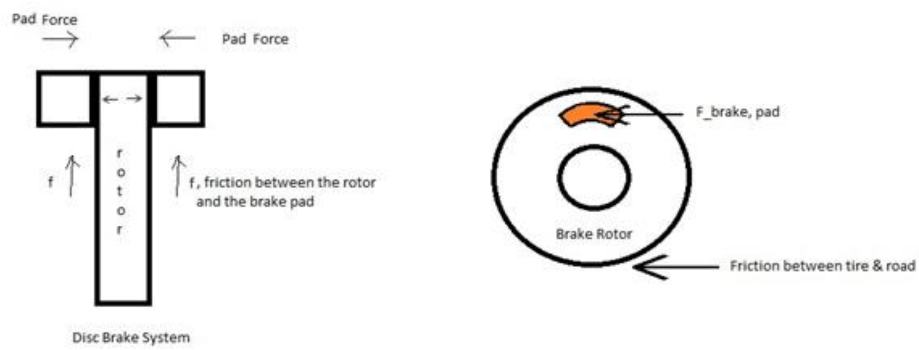

Figure 39. Simple schematic of disc brake

The physics behind locking up the front tires is established based on the assumptions that the brake disc is rigidly attached to the wheel and all components have 100%mechanical efficiency. See Appendix F for equations.

4.3.4 Test Results

Figure 40. Image of the broken piston rod from the original master cylinder

Originally, team five had the strategy to keep the same master cylinder since it gave a good ratio with the pistons of calipers by having a bore diameter of 0.5 inch. However, after thorough testing with the original master cylinder, team five realized that there was not enough force applied because of the broken piston rod as shown in Figure 40. As the master cylinder was being disassembled, the piston rod was found to be bent; which can be seen in the figure above. Thus, team five created a new piston rod to replace the bent one. With the change, it was assumed now that the full force can now be applied to the master cylinder to meet the goal since theoretically, the calculations stated the goal should be met with the original master cylinder. The result shown below show otherwise:

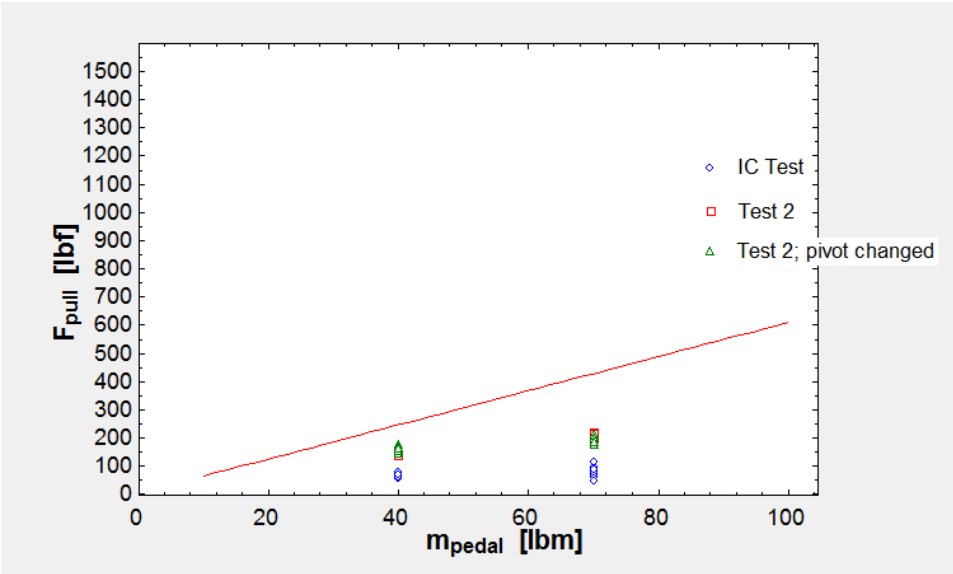

Figure 41. Test of car with original master cylinder.

The red line in Figure 41 contains the theoretical values of the amount of pulling force with a 35% of uncertainty as a function of the amount of mass applied on the brake pedal. The vehicle with its initial conditions (IC) was tested with the bent piston installed in the original master cylinder. The second test was done twice with the second time implementing the increase pivot ratio between the center line distances from the brake pedal to the shaft and the shaft to the pivot point. In addition, the purpose of the second test was to determine if the original master cylinder could still be used even with the new improvements. However, team five did not find significant improvement on the pulling force due to a severe leakage from caliper.

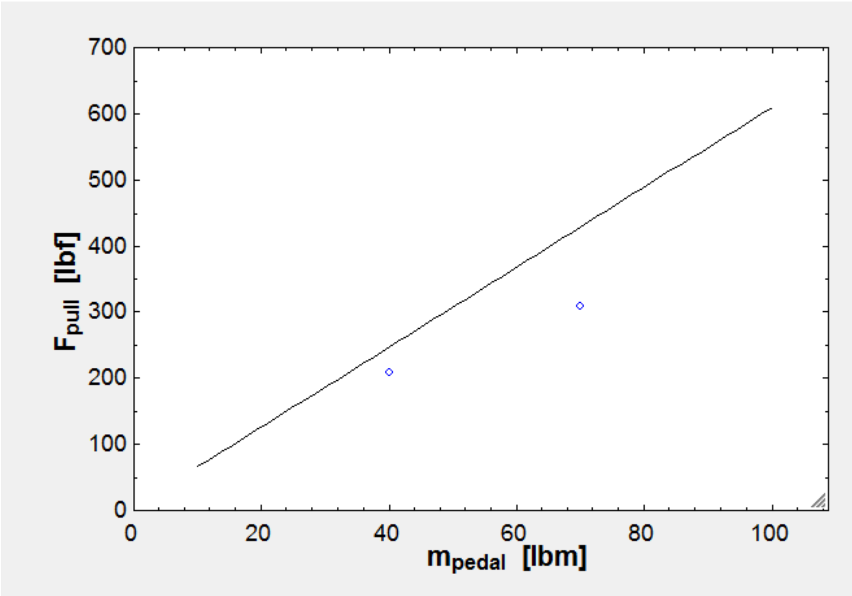

Figure 42. The testing results following the installment of the new master cylinder with twice the stroke (Test 3).

The results with the calipers and washers replaced, as well as the new master cylinder installed, are as shown in Figure 42. Only one data point in blue was indicated to show the averaged value at different forces applied on the pedal, 40 and 70 lbf. Neglecting minor pressure loss from bleed screws and replacing the pedal spring with softer stiffness, experimental data indicated closer to theoretical values within 20-25% error. See Appendix Q for testing data.

4.3.5 Final Design Results

Figure 43. New design of brake pedal

Team five had 29.2% of force increase after add a block to the lever arm. Based on the trend in our calculation, team five found out that increasing the brake pedal lever 3 x 3 inches on the lateral and vertical axis can compensate a suitable increase on the pulling force from test 3. Since the lever is a two force body structure, team five designed to cut the original block and weld an additional block piece to the original block so the brake pedal can be located beyond the pivot point where the master cylinder is attached. The implemented design can be seen above in Figure 43. See Appendix S for pedal design analysis.

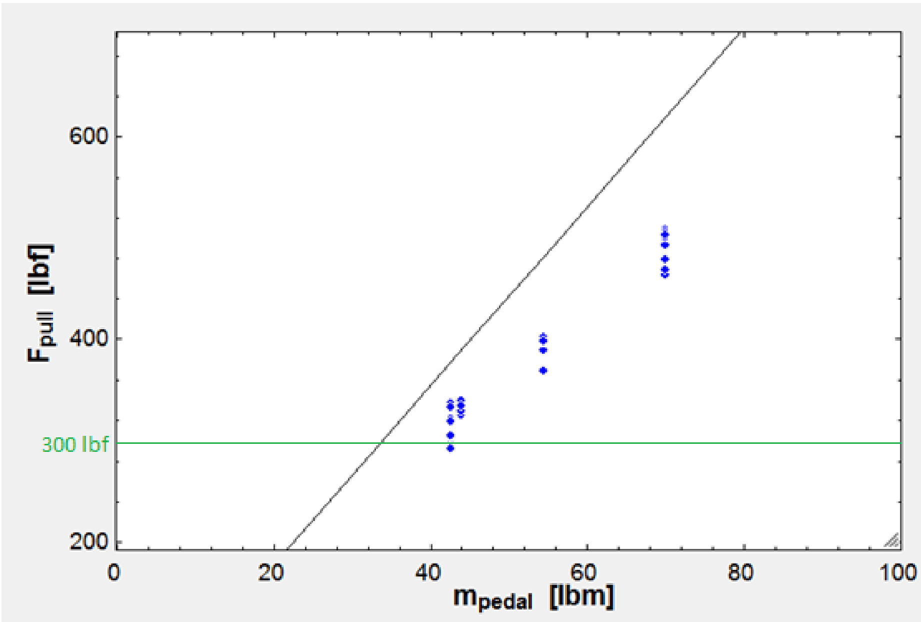

Figure 44. Test results with new design

Test results with the final design showed that the pulling force of the car with front brakes applied exceeds 300 lbf when applying 42 lbf. The industrial standard of 40 lbf applied on the pedal that team five had originally agreed on was based on a seat height of 13 inches. Since our seat height was not 13 inches but slightly shorter, the new applied force was not 40 lbf but 45 lbf or more with the assumption of a linear relationship between the seat height and force applied to brake pedal. Therefore, team five successfully reached our specification as shown in Figure 44.

Figure 45. New master cylinder attached

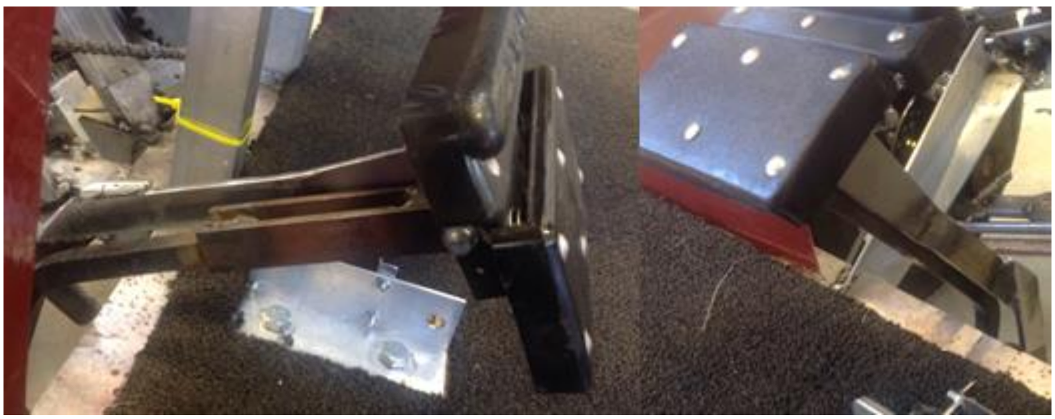

Figure 46. Brake pedal with parking brake

Overall, design decisions were focused on replacing damaged parts and improving the original structure based on mathematic calculations. Parts were replaced and cleaned to provide a greater force efficiency and an avoidance in the pressure loss by the fluid leakage. Mathematical calculations enabled the length increase, in the vertical and horizontal axis, of the brake lever arm to be optimized. Thus, team five's improvements with the largest impact were the vehicle's master cylinder and brake lever arm. Photos of the final design with parking brake attached are shown in Figure 45 and 46.

4.3.6 Stopping Distance and Time

The Calvin Bolt 3.0 was tested on the asphalt road outside the engineering building to check how much the vehicle stops with the new design. According to our test, on a flat surface (dry asphalt) with linear distance, it took the vehicle 2.77 seconds to stop with a stopping distance of 21 feet and 1 inch with a speed of around 17±3 mph. Although the speed of the vehicle has a maximum velocity of 25 mph, team five did not reach it on purpose because of a heating issue with its electrical switch module; as the vehicle reaches its highest speed, the plastic surrounding the copper sensors within the directional switch module begins to melt. On the final test before senior design night, the plastic melted so much that the original forward switch malfunctioned. To still have demos the following evening, for senior design night, the directions were switched which left the vehicle in its current position – only being able to move forward. It is recommended that a new module is perhaps bought or time, which team five did not have, is spent on resolving the issue.

Theoretically, stopping distance of the car with 17 mph provides the distance around 14 ft (Parker). Compared to what we obtained from the Calvin Bolt, the reality is about 35% off in average; team five expects the results can be improved once the accurate speed of car is measured. Also, team five observed that the tires of the Calvin Bolt skidded on the road when applied the brakes. Thus, the braking system of Calvin Bolt is effective.

4.3.7 Implementation - ABS

Since there are two common applications of antilock braking systems implemented onto vehicles, the components of the system are essentially the same. Wheel speed sensors are placed on a toothed wheel that is located alongside the wheel one wishes to control; this toothed wheel will rotate at the same speed as the vehicle wheel (Antilock Brake Systems). As both wheels spins, a pick-up coil (consisting of a magnet and wire) are used to obtain magnetic pulses in the form of current from the toothed wheel (Antilock Brake Systems). These pulses are then monitored by the ECU and compared to the pulses coming in from the other controlled wheels (Antilock Brake Systems). When a wheel is about to lock up and begin skidding, its speed is increased slightly more than that of the other wheels; the job of the ECU is to notice and act upon these increased speeds (Antilock Brake Systems). Once noticed, the ECU then activated the antilock system itself by sending signals to a solenoid which closes a valve that affects the specific wheel's brake line thus prevent a lock-up (Antilock Brake Systems). As mentioned earlier, there are multiple ways of implementing ABS onto a vehicle, however, the most common alternatives are either on all four wheels (also known as a four-channel ABS) or on the rear wheels (a two-channel ABS) (Nice 2000). However, there is a third alternative, see Figure 47 below, which takes into account the rear axle and the front two wheels (a three-channel ABS) (Nice 2000).

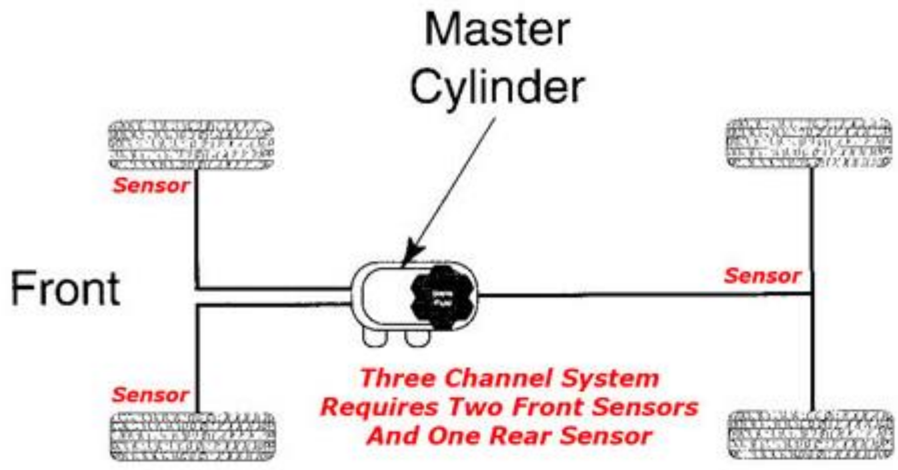

Figure 47. Basic outline of a three channel ABS system.

http://www.counterpersontraining.com/index.cfm?go=lms.module&moduleid=82&mode=train&contentIndex=6&topicId=319

As a part of the research for the system, team five spoke with two electrical engineers, Monica Groenenboom and Yoon Kim. Through their conversations, team five learned the unfeasibility of implementing ABS as well as power steering into the overall improvement design of the Calvin Bolt. This unfeasibility was primarily due to the lack of time, funds and knowledge. If such a system was to be implemented, it was recommended that implementing ABS or power steering would have to be a whole senior design project on its own. For this reason, ABS and power steering (as previous mentioned) will not be designed nor implemented into the Calvin Bolt 3.0.

If a group should want to take on the challenge as a senior design project, the parts needed are described in the previous paragraph as how ABS works is written. In addition, with the current braking system, it is recommended to implement a three-channel ABS with the two front disc brakes and the rear axle as its third channel. As for whether the ECU of ABS and power steering should be combined, the decision depends on its trade-offs. If the ECU's are combined, cost and maintenance will be decreased, along with the possibility of decreased coding. However, if the ECU's are separate, cost and maintenance are increased but if one system malfunctions, not only will the other work, but the malfunctioning one can easily be determined unlike the situation in which the ECU's are combined into one.

4.4 Version Control Software

4.4.1 Research

Only knowing the term "design documentation software," team five discovered not only the purpose of the software within a company and project, but its capabilities as well. After learning its common vernacular, "Version Control" software, the team became aware of how version control software helps companies keep track of changes and any progress made throughout a design process (Frozenlock). Through conversations from advisors, team five also learned there is a wide variety of version control software to choose from.

4.4.2 Alternatives

Team five originally came down to two alternatives for its version control software:

GitHub is commonly used to help developers work on team projects, personal projects, and with open source technologies (GitHub). The pluses of GitHub are that it is free. However, it does not do well with multiple users. It also requires strong C programing skills with is something team five does not properly have.

Adept, the official name of the software provided by Synergis, is commonly used to help users "find, manage, and share" various documents from Microsoft Office to CAD files (Synergis.com). The pros of Adept are that it is made for large and small companies, its feasibility is easy, and its flexible in the different types of files. The cons of Adept are that it is not free and there is a limited amount of seats available.

After deciding on Adept as the optimal choice, team five correlated a conference call with the representatives of Adept to discuss the necessities required to obtain a license. Unfortunately, for reasons discussed in the following section, the likelihood of obtaining an Adept license is very much unlikely. Therefore, team five added an additional two alternatives to its original list:

Vault, a data management software provided by Autodesk, allows one to manage design data, CAD revisions, documentation and other development process involved in a design process. There are three versions of the software, Vault Basic, Workgroup and Professional. However, team five is considering the Vault Basic as one is its alternatives due to the cost of the software.

Lastly, all files related to the Calvin Bolt project have been placed in the team S drive which Calvin engineering has promised to back up. Nathan Swaim has also made a backup of all files related to the project. See Appendix T for information on accessing the S drive and contacting Nathan.

4.4.3 Decisions

Taking into the considerations of cost, usability, and variability, Vault Basic is the chosen version control software team five will implement into their project. The original chosen version control software was Synergis. However, as mentioned in the section before, after meeting with representatives, implementing Adept for one year would cost a little over sixteen thousand dollars; overstepping the budget by a long haul. As for the other alternatives, even though they were available at little to no cost, Vault can hold documents of various kinds as well as CAD documents thus eliminating the need for a nostalgic flash drive. In addition, Github, as mentioned earlier, requires some C language coding and with team members that all lack proficient skills in C language, choosing Github would have turned out to be a nuisance rather than a form of aid.

4.4.4 Implementation

In choosing Vault as the chose version control software, team five was expecting to implement Vault Basic. However, Vault Professional ended up being installed rather than Vault Basic. This decision was made by the engineering department. With Vault Professional, the engineering department hopes to use team five as a tester group for a possible future requirement of future teams implementing version control into their design projects as a way to effectively document and manage their projects. In addition, version control is heavily used in the automobile industry thus giving students an opportunity to get ahead of the game.

The version control software will be implemented into every aspect of the designing process. All aspects include the exchange of emails, meeting minutes, CAD drawings, calculations and documents. The biggest implementation of the control software will be indicating changes made to the CAD drawings done for the steering system. Before team five could create new designs, the original steering system needed to be drawn via CAD software. Once this task is completed, team five will use the revision tracking feature of Vault to track the revisions made toward the new steering system design. The braking system will not have any CAD drawings in general, therefore, only calculations, pictures, testing results and any other documents pertaining to the braking system will be stored.

4.45 AutoDesk Vault

In order to effectively pass off the Calvin Bolt to the next senior design group, documentation software needed to be used in order to make sure the next senior design group could pick up right where the last senior design team left off.

Autodesk Vault was used to document everything done in the CAD model. Once all the original parts for the car had been made, they were all put into a single folder along with an assembly file. For more information on how to use Autodesk vault in inventor, see appendix P.

4.4.6 Documentation of Changes made to the Design

For information on changes made to the CAD model, see appendix R.

5 Business Plan

5.1 Market

The market for the developed systems was other automobile companies. The competitors would have been other mechanical engineering firms that are developing similar systems. The market objective would be to develop systems that are just as reliable as other competing systems but cost far less.

To compete with these companies, team five would assemble much of this project by hand and volunteer labor. Team five would also keep its market highly specific so that it can compete with as few firms as possible.

Team fives chief competitors were Nexteer and CooperStandard. Both companies are headquartered in Michigan and are leaders in their fields of design.

Nexteer is a small engineering company based in Saginaw Michigan. It is a world class supplier of power steering systems. In 2015, the company did 2.8 million dollars' worth of business. Two million of those dollars came from the sale of electric power steering systems. [1]

CooperStandard is also a Michigan car parts company which specializes in braking systems. Last year CooperStandard did 32. 7 million dollars' worth of business. [2]

Both companies design competent products. Their names are also far more known than team five. Thus the marketing strategy is as follows.

1. There will be a focus on reaching out to buyers and meeting with them face to face. This means scheduling interviews and often traveling in person to their facilities to showcase the product.
2. Team five would reach out to major car companies in Michigan such as Ford and General Motors. Specific small size model cars will be targeted such as the Ford Ka and the Chevy Sonic & Spark. [3]
3. Lastly, team five would place an emphasis on online availability. A design guide would be placed on the team website which can be viewed for free.
4. Team five would take advantage of online advertising. A short two-minute video advertising the product would be placed online.

5.2 Cost Estimate

See Appendix D for summary of cost. Team five estimated a full cost in improving steering and breaking system is now modified. If each unit costs 500$ to produce, then the total cost of production for a single unit will be around 9000$. Based on a MARR of 15%, team five will make a profit with a 15% markup.

Table 2. Cost estimate for components needed for project

Cost Estimate	UNITS	PRICE	TOTAL	STORE
Low Carbon Steel Rod (8920K155)	1	$7.72	$7.72	McMaster Carr
Finished Bore Sprockets (6280K143)	1	$11.88	$11.88	``
Finished Bore Sprockets (6236K29)	1	$48.52	$48.52	``
Caliper (item # 7240)	1	$68.99	$68.99	Jake's Lift Kits
Parking Brake	1	$0.00	$0.00	Calvin Metal Shop
Brake Fluids (grade 3)	2	$19.99	$39.98	O'Reilly Auto Parts
Copper Washer (item # 5795)	10	$0.69	$6.90	NAPA Auto Parts
1/8 Brass Plug (item # 748358)	1	$2.69	$2.69	Lowe's
Master Cylinder (item # 260-11097)	1	$121.96	$121.96	Amazon.com
Vault Professional (yearly licensed)	1	$695	$695	Autodesk
Total			$ 1,003.64	

6 Future Senior Design Projects

Future senior design projects include the following:

1. **Redesigning the outer frame of the car to be aerodynamically efficient-**great mechanical project. Would require building a scaled model of the car which could be tested in the Calvin wind tunnel. Would also require a lot of machining.
2. **Speaker/Bluetooth/lighting System**-Great electrical project that would help make the vehicle something fun. Could also design the system so it interfaces with the raspberry pie currently on the dash board.
3. **Self-damping seats**-These kinds of seats can be found in luxury vehicles. They allow the rider to have an almost bump less experience. This project requires some background in vibrations but is attainable in a school year. Requires some background in vibrations.
4. **Suspension system with eliminated bump steer**-This project would require rearranging the chaise significantly. See appendix O for more information.
5. Developing a **gas/electric engine capable of getting the Calvin Bolt up all the hills** on campus-great mechanical/mechanical-electric project. A steam engine is also an option. This issue may also be fixed by **improving the torque conditions** of the vehicle.
6. **Power steering-**This project would also go well with the controls class. For power steering, one would most likely have to completely redesign the chaise on the front of the car as one would need to find a place for the motor.

7. **ABS Design and Implementation-**This is an excellent project if one is taking controls. This project is also capable of being completed in a school year. Something to consider with this project is also adding rear breaks to the Calvin Bolt.
8. **Electric breaks**- Similar to ABS brakes but scaled down. Electronic breaks would replace the current hydraulic brake calipers with electronic actuators. This system is beneficial since it is not dependent on hydraulic fluid.
9. **Making the car a DMV certified registered vehicle**- This could take years to complete. This would require seatbelts, mirrors, signal lights, and making sure the Bolt meets all the DMV safety standards.

Figure 48. Aerodynamically efficient car. http://www.automotiveworld.com/wp-content/uploads/2013/02/Volkswagen-XL1.jpg

Figure 49. Bluetooth Stereo System. http://sonyglobal.scene7.com/is/image/gwtprod/a42ea0b8e118fc1af81d9309a975a1a7?fmt=pjpeg&wid=1014&hei=396&bgcolor=F1F5F9&bgc=F1F5F9

Figure 50. 3D printed engine. https://3dprint.com/wp-content/uploads/2015/01/en2.png

7 Conclusion

7.1 Evaluation

Team five has found the Calvin Bolt 3.0 senior design project to be feasible and functional with the elimination of the ABS and power steering, along with the reduction of priority for the parking brake pedal. Although there are multiple areas in need for improvement on the Calvin Bolt 3.0 as whole, downscaling the design project to the redesign of the braking and steering system allowed the focus of team five to be centralized onto the two systems (in addition to the version control software) thus resulting in highly reliable and functional systems. With a team of four mechanical concentrations, designing these systems with an electrical foundation will definitely open up not only difficult roads ahead but opportunities for growth and learning.

7.2 Maintenance

The braking system is fully functional in terms of providing a suitable stopping distance and time; these values can be seen in section 4.3.6. However, despite the vehicle's functionality, there can be future improvements on the braking system along with other improvements as mentioned in section 6. During the last days of testing for the vehicle, brake fluid leakage from the calipers occurred creating the first improvement in determining a way to either minimize or eliminate the leakage. Small amounts of brake fluid kept leaking from the bleed screws despite the addition of sealing cream on the screws. Team five did not consider the leakage a major issue since the leakage is only a couple drops of brake fluid. For this reason, team five recommends to keep the reservoir filled all the time.

Secondly, there is a problem in wheel brackets. Screws that hold the lower arm on wheel brackets are not the same length. The screws on the left side of wheels are shorter than the right side; this issue may cause potential collapse of the vehicle's suspension.

Thirdly, there was a serious heating issue with directional switch module. More details of this issue are mentioned earlier in section 4.3.6.

As for the steering system, future improvements aside from a new senior design project, include the following:

1. Reducing friction between the gears and the steering rack.
2. Increasing the aptitude of the steering wheel in order to allow the driver to sit further forward in the car.
3. Aligning the steering rack so that it is parallel to the suspension.

In regards to the version control software, Vault, no improvements could be thought of.

8 Acknowledgements

The following list are the name of people who support and advice for designing Team 5's design project as well as the content of their contribution.

2015-2016 Senior Design Team 10- Christine De Zeeuw, Daniel DeVries, Laura Boluyt, and Vincent Rovedatti

Professor Jeremy VanAntwerp – Team Advisor

Professor Ren Tubergen – Mechanical design consultant

Professor Yoon Kim – Control system consultant (fall)

Professor Monica Groenenboom - Control system consultant (fall)

Troy M. Kinne – Industrial consultant (fall)

Phil Jasperse – Metal shop supervisor

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10 Appendices

Appendix A - Force Body Diagram of Car and Derivation of Critical Velocity

A car is traveling down a road at 20 mph. What is the sharpest turn that car can make without tipping over?

A car that is about to tip while in a turn has three forces acting on it. First the centripetal force which causes the car to turn. Second, the normal force which is the weight of the car and is exerted through the tires to the ground. Lastly, the fiction force which acts against the centripetal force and is dependent on the size of the normal force. [4]

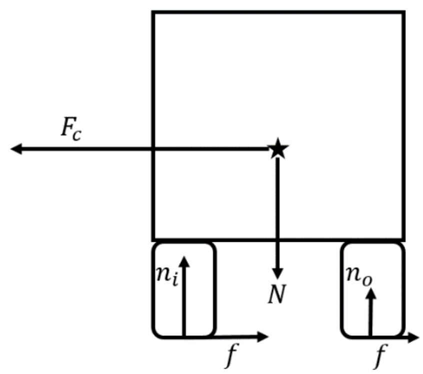

Figure 51. Diagram showing the forces that are exerted on a vehicle as it turns

For a structure to be in static equilibrium, the sum of the forces and the sum of the moments must be zero.

$$\sum F_x = 0$$

$$f_i + f_o = F_c$$
$$f_i = n_i\mu$$
$$f_o = n_o\mu$$
$$n_i\mu + n_o\mu = F_c$$

$$\sum F_y = 0$$

$$n_i + n_o = N$$

The moments are summed as follows,

$$\curvearrowright \sum M_a = 0$$

$$F_c y - n_o x + N\frac{x}{2} = 0$$

$$m\frac{v^2}{r} y - n_o x + N\frac{x}{2} = 0$$

When the car tips, the normal force exerted by the car in the inside wheel goes to zero and the cars weight shifts to the outside wheel. The car is also assumed not have angular acceleration. Thus:

$$N\frac{x}{2} = n_o x - m\frac{v^2}{r}y$$
$$mg\frac{x}{2} = mgx - m\frac{v^2}{r}y$$
$$g\frac{x}{2} = gx - \frac{v^2}{r}y$$
$$y\frac{v^2}{r} = g\frac{x}{2}$$
$$\mathrm{v}^2 = gr\frac{x}{2y}$$
$$v = \sqrt{gr\frac{x}{2y}}$$

The tipping velocity is independent of the mass of the car. Instead, it depends on the location of the center of gravity and radius of the turn. From this, fora maximum speed of 20mph and assuming x=.70 meters and y=.50 meters, the max turn radius at such a speed is 12 meters. [5]

The critical velocity is dependent upon the speed of the car, the sharpness of the turn and the location of the center of mass. Since the center of mass changes with a live load, the control system must be calibrated to sense changes in the car's center of mass in order to prevent overcompensation.

The greatest cause of potential danger in the power steering system is a programing error that results in an overcompensation by the AC motor. The car's radius of turn must be limited by the control system as it reads the speed of the car as well as the car's center of mass.

Appendix B - Tipping Force EES Calculation

The power-steering system must be designed properly to prevent rollover. Rollover is dependent upon the speed of the car, the sharpness of the turn, and location of the center of mass. This relationship is shown in the following equation:

$$v_t{}^2 = r_t s g, \qquad s = \frac{w}{2h}$$

Where w corresponds to the width of the car and h corresponds to the height of the center of mass. A car is least likely to roll over when the center of mass is low to the ground, the car is wide, and the turn being made is wide.

```
"Tipping Force on the Car"
height_of_cg=.7 [m] "+-.1"
dist_from_tires_to_cg= .5 [m] "+-.2"
v=20 [mph]
v_crit=v*convert(mph,m/s)

turn_radius=2 [m]
g=9.81 [m/s^2]


v_crit^2=r*g*s
"r=turn_radius"
s=SSF
SSF=y/(2*x)
y=height_of_cg
x=dist_from_tires_to_cg
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$dist_{from,tires,to,cg}$ = 0.5 [m]	g = 9.81 [m/s^2]
$height_{of,cg}$ = 0.7 [m]	r = 11.64 [m]
s = 0.7	SSF = 0.7
$turn_{radius}$ = 2 [m]	v = 20 [mph]
v_{crit} = 8.941 [m/s]	x = 0.5
y = 0.7	

This assumes the car will only make a turn on a level road and will also not change its radius of turn when doing so.

Appendix C - Team Five Schedule

Table 3. Deadlines of team's project

Week	Dates			Calendar	Project Deadlines
1	29-Jan	-	4-Feb		
2	5-Feb	-	11-Feb		Brake spec decision period
3	12-Feb	-	18-Feb		
4	19-Feb	-	25-Feb		
5	26-Feb	-	3-Mar		
6	4-Mar	-	10-Mar		Brake calculation completed
7	11-Mar	-	17-Mar		Brake test layout was designed
8	18-Mar	-	24-Mar	Spring break	
9	25-Mar	-	31-Mar		
10	1-Apr	-	7-Apr		Cad model completed
11	8-Apr	-	14-Apr	Easter weekend	Brake test
12	15-Apr	-	21-Apr		Brake design installed
13	22-Apr	-	28-Apr		Calvin bolt drive test, New Cad model complete
14	29-Apr	-	5-May		Rough draft of Final Report completed, New Steering assembly complete
15	6-May	-	12-May	Last week of classes	Final Report edited and turned in

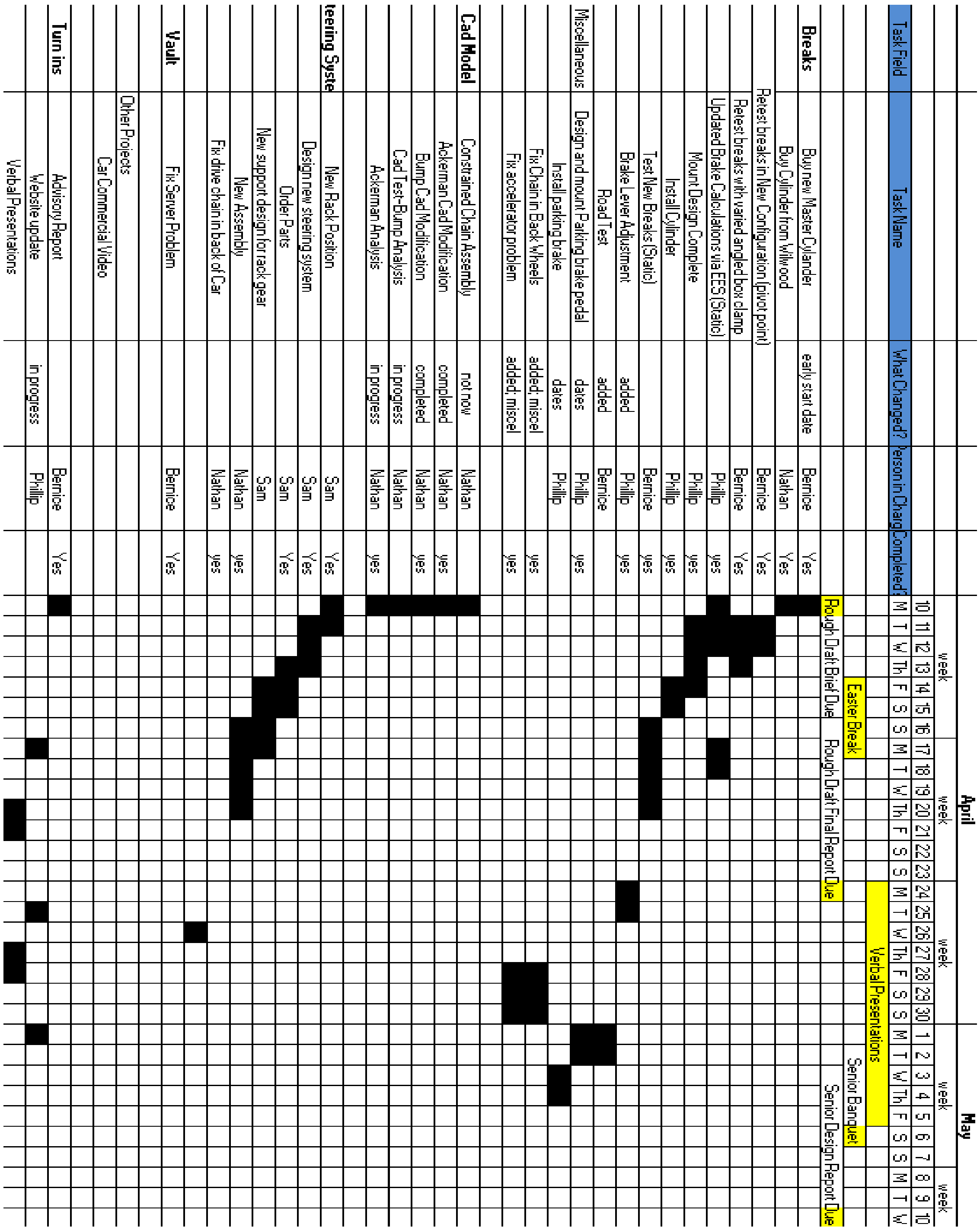

Figure 52. Team's Gantt chart for April and May

Team five decided to make a separate Gantt chart as shown in Figure 52 so that each of team members became fully responsible for what they were charged of and show full participation to the project.

Appendix D - Estimate of Variable Costs

Table 4. Table of estimated cost of production

Fixed & Variable Costs			
Employee Cost			
	Number of Employees	4	
	payroll	$5.00	/h
	insurance	$3.00	/h
	sickness & maternity	$3.00	/h
	Total	$44.00	/h
Factory Expenses			
	Inspection	$1.00	/h
	purchasing	$50.00	/h
	(based on 500$ budget)		
Company Expenses			
	R & D	$2.00	/h
	Marketing	$3.00	/h
Days of Operation		300	days
Cost per Unit		$8,880	
Total Cost		$266,400	
Units Sold per Year		30	
Price per Unit		$8,880	/unit
Total Revenue w Markup		$266,400	
Cost per Unit w Markup		$10,478	
Markup		0.18	
Total Revenue		$314,352	
Total Profit		$47,952	
Sale Price		$10,478	/unit

Appendix E – Brake Rotor Inspection Result

Brake disc (rotor) was inspected for its range of thickness variation on multiple location. Inspection standard was followed by *Automotive service: Inspection, maintenance, repair*.

Figure 53. Thickness measurement of rotor with a vernier calipers

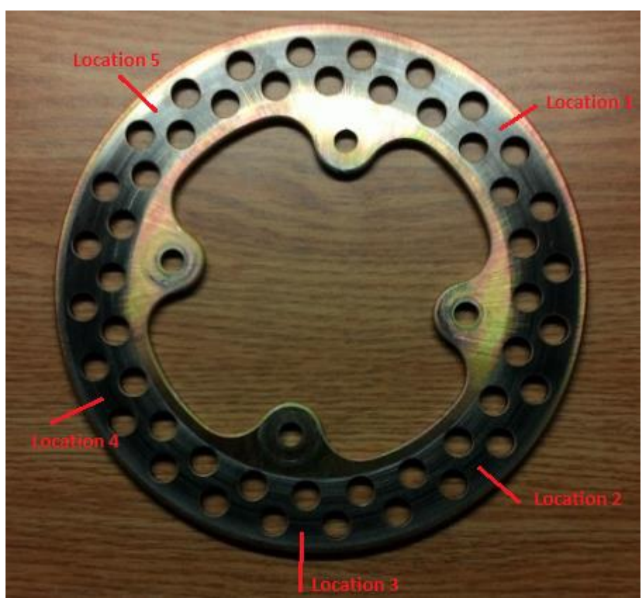

Figure 54. Measure of thickness variation at multiple locations

Table 5. Thickness results

Location	Size(inch)
1	0.1865
2	0.1870
3	0.1870
4	0.1870
5	0.1865

As a result, all measurements are greater than 0.015 inches, and the thickness variation is within 0.0005 inches. Therefore, the service condition of the rotor is good.

For runout condition, after multiple drive tests, team five did not observe any damages on the rotor as the width stays the same as before. Thus, team five concluded that the rotor of current brake system does not need to be replaced anyhow.

Appendix F – Braking Force Calculations

```
"!Decision variables"
person_front = 1
person_back = 0
m_pedal = 40[lbm]
d_mc_bore=5/8 "master cylinder piston outer diameter"
d_caliper_bore = 1 [in]
R_tire = (20.5/2) [in] "radius of tire"
r_rotor_caliper=3.5[in] "!caliper piston diameter"

"!Known"
m_car={1310.45} 1386.35 [lbm]
m_car_front=m_car*(2/5) "!2/5 is an assumption"
m_car_back = m_car*(3/5) "!3/5 is an assumption"

m_person_front = 190[lbm] *person_front
m_person_back = 190[lbm] *person_back

m_car_front_total=m_car_front+m_person_front "total mass applied"
m_car_back_total= m_car_back+m_person_back

g=32.17[ft/s^2] "gravitational acceleration"
x=32.17 [lbm*ft/lbf-s^2] "pound force conversion factor"
A_pad=2.151 [in^2] "Area of a brake pad"

"!Assumptions"
"1. The Calvin Bolt travels a path at uniformly constant velocity."
"2. Path of the Calvin Bolt is ideally flat surface that applies the uniform friction throughout."
"3. For the hydraulic force, secondary factors, such as viscosity or fluid velocity, are ingnored."
"4. All estimation are based when any forces and pressures are fully conserved in the system."

"!Resisting Forces"
"Friction coefficient of a brake pad"
theta = 25 [deg]
mu_pad = tan(theta) "static friction coefficient between the rotor and the pad"

"Master cylinder to Calipers"
A_mc=pi*((d_mc_bore/2)^2) "cross sectional area of the master cylinder"
A_caliper=pi*((d_caliper_bore/2)^2) "cross sectional area of the caliper"
F_pedal_spring = 0.4895 [lbf] "spring force applied around the pivot"

F_pedal = m_pedal * g / x

a = 31 [deg] "pedal angle"
b = 15 [deg] "moving angle"
F_pedal_x = F_pedal*cos(a+b) "x component force of pedal; newton's 2nd law"
F_pedal_y = F_pedal*sin(a+b) "35 deg is for the moving angle of the pedal"

z = 8.75[in]*cos(b) "horizontal distance of the pedal before pressing it"
F_pedal_x*(7.625)[in] + F_pedal_y*(z+3[in])-F_pedal_spring*(3[in])= F_mc*(2.1253-0.625) [in]

F_caliper/A_caliper=F_mc/A_mc
P_hydraulic = F_caliper/A_caliper "hydraulic pressure in brake hose"
```

"Pad to rotor"
F_pad = P_hydraulic*2*A_caliper "force applied by a pad"
F_clamp = 2*F_pad "Clamping force"
f_pad_friction = F_clamp*mu_pad "total frictional force by the brake pad"
T_rotor = f_pad_friction * (r_rotor_caliper)
T_wheel = T_rotor
F_tire_front_one = T_wheel/R_tire "Force exerted on front tire; only one side"
F_tire_front = F_tire_front_one*2

"Tire to road"
mu_tire_ground = 0.3 "Rolling resistance if the car is sliding. skidding"
mu_tire_ground_rolling = 0.01

W_car_front = m_car_front_total*g/x
W_car_back = m_car_back_total*g/x

f_car_front = mu_tire_ground*W_car_front "resistanting friction by the car itself."
f_car_back = mu_tire_ground_rolling*W_car_back "no brakes in the car."

"Force required to pull the car"
F_pull_skidding = mu_tire_ground*W_car_front +f_car_back "from Test 1"
F_pull = ((F_tire_front) + f_car_back)*0.3 "! 0.3 is an uncertainty constant from misalignment of parts, rule of thumbs, etc"

$a = 31$ [deg]	$A_{caliper} = 0.7854$ [in^2]	$A_{mc} = 0.3068$ [in^2]
$A_{pad} = 2.151$ [in^2]	$b = 15$ [deg]	$d_{caliper,bore} = 1$ [in]
$d_{mc,bore} = 0.625$ [in]	$F_{caliper} = 921.3$ [lbf]	$f_{car,back} = 8.318$ [lbf]
$f_{car,front} = 223.4$ [lbf]	$F_{clamp} = 3685$ [lbf]	$F_{mc} = 359.9$ [lbf]
$F_{pad} = 1843$ [lbf]	$f_{pad,friction} = 1718$ [lbf]	$F_{pedal} = 40$ [lbf]
$F_{pedal,spring} = 0.4895$ [lbf]	$F_{pedal,x} = 27.79$ [lbf]	$F_{pedal,y} = 28.77$ [lbf]
$F_{pull} = 354.6$ [lbf]	$F_{pull,skidding} = 231.7$ [lbf]	$F_{tire,front} = 1174$ [lbf]
$F_{tire,front,one} = 586.8$ [lbf]	$g = 32.17$ [ft/s^2]	$\mu_{pad} = 0.4663$
$\mu_{tire,ground} = 0.3$	$\mu_{tire,ground,rolling} = 0.01$	$m_{car} = 1386$ [lbm]
$m_{car,back} = 831.8$ [lbm]	$m_{car,back,total} = 831.8$ [lbm]	$m_{car,front} = 554.5$ [lbm]
$m_{car,front,total} = 744.5$ [lbm]	$m_{pedal} = 40$ [lbm]	$m_{person,back} = 0$ [lbm]
$m_{person,front} = 190$ [lbm]	$person_{back} = 0$	$person_{front} = 1$
$P_{hydraulic} = 1173$ [psi]	$r_{rotor,caliper} = 3.5$ [in]	$R_{tire} = 10.25$ [in]
$\theta = 25$ [deg]	$T_{rotor} = 6014$ [in-lbf]	$T_{wheel} = 6014$ [in-lbf]
$W_{car,back} = 831.8$ [lbf]	$W_{car,front} = 744.5$ [lbf]	$x = 32.17$ [lbm*ft/lbf-s^2]
$z = 8.452$ [in]		

Appendix G - Physical and Mechanical Properties of Materials

Table 6. Characteristics of materials

	Al 6061	Steel 1008	Steel 1010
Density	0.0975 lb/in³	0.2844lb/in³	0.284lb/in³
Brinell Hardness	25	86	95
Tensile Strength, Ultimate	13000 psi	49,000 psi	53,000 psi
Tensile Strength, Yield	7000 psi	41,500 psi	44,000 psi
Modulus of Elasticity	10000 psi	27557-30458ksi	27557-30458ksi
Shear Modulus	3740 ksi	11600ksi	11600ksi
Shear Strength	10000 psi	-	-

Sources: www.matweb.com

Appendix H - Turn Radius

The turn radius was measured by hand using a tape measure. Having turned the wheel to the furthest right position, the distance perpendicular to the turning wheel was measured 12 times. The results are shown in figure 55 below.

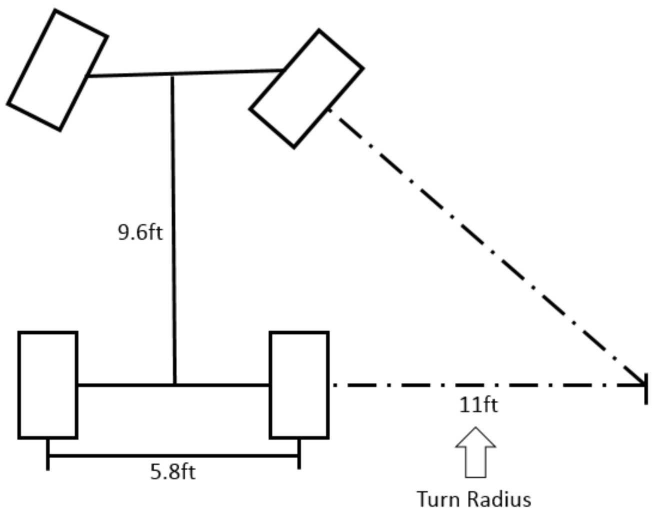

Figure 55. Diagram of the turn radius.

Table 7. Measurements and uncertainty for turn radius.

Measurement (ft)	
11.04	10.95
11.2	12
10.5	11.3
12.3	12.5
10.8	11.25
11	11.7

Table 8. The average value and uncertainty are shown below.

	Feet	Meters
AVERAGE	11	3
STANDARD DEV	0.6	0.2
UNCERTAINTY	2	0.5

Appendix I - Estimate of Power Required by the Motor

If the center of mass is assumed to be in the center of the car, then the weight of the car and the passengers can be assumed to be equally distributed.

Table 9. Weight values for the car

Weight of Car		
Total	**2215**	lb
5 People	800	lb
Box 1	0.25	lb
Accel Pedal	0.2	lb
Door (4)	23	lb
Box 2	5.25	lb
Box 3	0.15	lb
BtB Cover R	7.75	lb
BtB Cover L	7.55	lb
BtB (4)	165.2	lb
Car	2005.65	lb

The weight of the car with five people in the car is estimated to be around 2200lbm with an uncertainty of +-300lbm. With this assumption. The front wheels are assumed to bear one half the weight of the car.

When the car turns, the wheels must overcome the force of friction. If the coefficient of friction between the ground and the wheels is estimated to be around .6, then the result is the following.

$$F_{steer} = F_{friction} = \mu F_{car\ on\ front\ wheels}$$

Equation 3

Where the force on the front wheels is estimated to be 1100 lbm. Multiplying this by gravity yeilds36000 lbf which is equal to 160kN. Multiplying this by the coefficient of friction yields a force of 96kN to turn the car.

The power required to turn the car is simply the distance the interior shaft needs to move in order to make a turn.

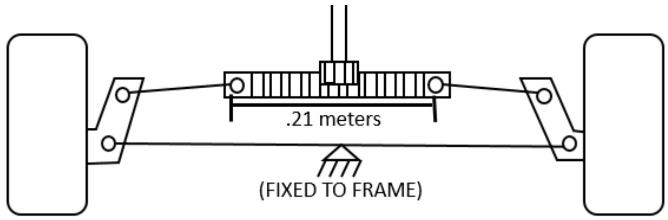

Figure 56. Diagram of rack and pinion system

To make a turn, the car must be capable of turning from completely right to completely left. This is a work output of 20kNm. This turn must be completed in a short time span. An adequate response time is less than 10 ms [6]. This means the power output of the motor needs to be around 2000 kW.

Appendix J - Ackerman Steer

Ackerman Steer is a geometric constraint which allows a vehicle to turn without slippage. In order for the front turning wheels to turn without slippage, the front inside and outside wheels must be able to rotate about a point which is similar to the one illustrated in figure 57 below.

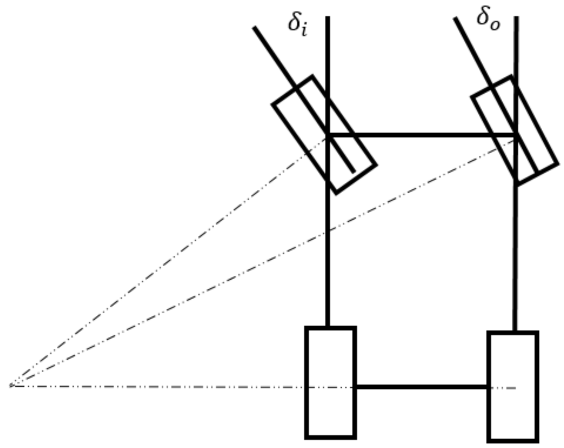

Figure 57. Ackerman steering about a point

What this means is that the inside wheel will turn more sharply than the outside wheel. Notice that the point of rotation is aligned with the back wheels. For the Calvin Bolt, Ackerman steering is dependent on the distance from the front to back wheels as well as the width of the car. The length to width ratio of the car was calculated to be .48. For more information on how this was calculated, see appendix B.

Ackerman steering is governed by the Equation 1 below when only the front wheels can rotate.

$$\cot(\delta_o) - \cot(\delta_i) = \frac{w}{l} \qquad \textit{Equation 4}$$

Where δ_i corresponds to the inside wheel turn and δ_o corresponds to the outside wheel turn. If both of these angles. If the inside angle were plotted against the outside angle, the resulting relationship would be shown for Ackerman steer.

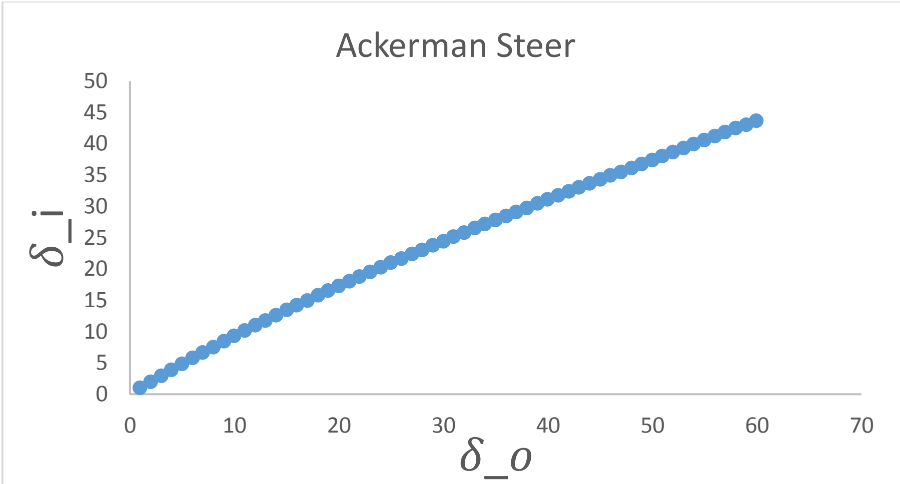

Figure 58. The Ackerman condition

Note that the above relationship is for when the car possesses true Ackerman steering. To correct the steering wheel geometry for the Ackerman condition, the condition illustrated in the drawing below needed to be true.

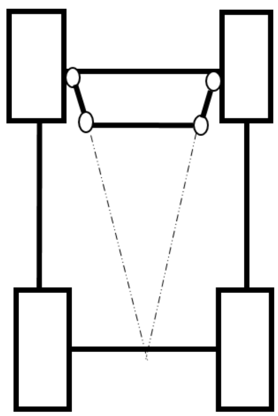

Figure 59-Ackerman geometric alignment

The joints from the tie rods and the tires must be set up such that two straight lines are drawn to the middle of the rear wheels' rack.

Appendix K - Wheel to Wheel Distances

The wheel to wheel length and width were measured using a tape measure. The wheel to wheel width was measured by placing the tape measure half way between the treads. For the wheel to wheel width, the distance was measured from the center of the wheel on the outside bearing. Multiple measurements were obtained in order to calculate uncertainty. The results are shown below.

Table 10. Wheel to wheel length & width

Length & Width of Car	
Length	**Width**
119.25	56.9375
119.4	56.90625
119.5	56.96875
119.4375	56.9375
119.4375	56.9375
119.375	56.875
119.5	56.9375
Average	
119.4	56.9
Standard Deviation	
0.08	0.03

The wheel to wheel length was found to be **119.4±0.05inches**.

The wheel to wheel width was found to be **56.9 ±0.05inches**. This gives the car a width to length ratio of **0.48 ±0.005**.

Appendix L - CAD Chain Assembly

Below is an image of the original CAD chain assembly that was constructed in inventor. The chain is composed of 72 links and over 150 constraints.

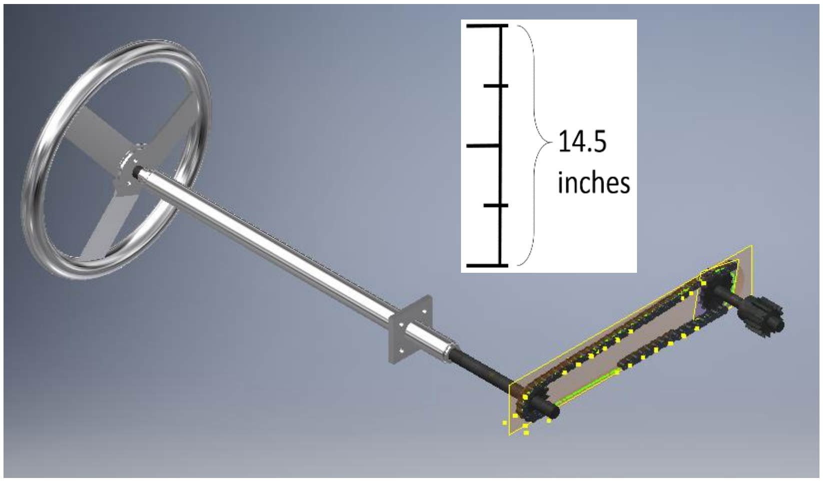

Figure 60. CAD chain assembly (-chain_assembly.iam)

Inventor unfortunately does have an easy way of creating and implementing a chain in inventor. The chain in figure 53 was created using the video found at the following link

https://www.youtube.com/watch?v=G4ZsCWFlvNc

The problem with this assembly is that the constraints overlap too much. It is best to constrain all the chain links to a single plane as much as possible.

Appendix M - Steering Degree Ratio

Table 11. Gear specifications used in tables 12 through 14

	Original shaft gear	rack gear original	rack gear 2	rack gear 3
teeth	12	16	22	38
bore	0.75	0.75	0.75	0.75
pitch	0.5	0.5	0.5	0.5
OD	2.17	2.81	3.78	6.33
DP	6.28	6.28	6.28	6.28
PD	1.91	2.54	3.52	6.05
		1.33	1.84	3.17

Table 12. Change in angle data for gear ratio 1.33

Ratio from gear to gear (1.33)						change in angle			
Right 1	Right 2	left 1	left 2	steering 1	steering2	Right tire	left tire	steering	Ratio
90.72	93.08	89.62	87.35	135.77	109.59	-2.36	2.27	26.18	11.30886
93.08	95.13	87.35	85.41	109.59	87.12	-2.05	1.94	22.47	11.26316
95.13	96.97	85.41	83.7	87.12	67.25	-1.84	1.71	19.87	11.19437
96.97	99.13	83.7	81.72	67.25	44.22	-2.16	1.98	23.03	11.1256
99.13	101.08	81.72	79.97	44.22	23.85	-1.95	1.75	20.37	11.01081
101.08	102.47	79.97	78.76	23.85	9.65	-1.39	1.21	14.2	10.92308
102.47	103.42	78.76	77.93	9.65	0	-0.95	0.83	9.65	10.8427
									11.09551

Table 13. Change in angle data for gear ratio 1.84

Ratio from gear to gear (1.84)						change in angle			
Right 1	Right 2	Left 1	Left 2	steering 1	steering2	Right tire	Left tire	steering	Ratio
90.54	92.06	89.8	88.32	137.82	114.41	-1.52	1.48	23.41	15.60667
92.06	93.81	88.32	86.65	114.41	87.71	-1.75	1.67	26.7	15.61404
93.81	95	86.65	85.53	87.71	69.81	-1.19	1.12	17.9	15.49784
95	96.96	85.53	83.7	69.81	40.56	-1.96	1.83	29.25	15.43536
96.96	98.59	83.7	82.21	40.56	16.6	-1.63	1.49	23.96	15.35897
98.59	99.74	82.21	81.17	16.6	0	-1.15	1.04	16.6	15.15982
									15.44545

Table 14. Change in angle data for gear ratio 3.17

Ratio from gear to gear (3.17)						change in angle			
Right 1	Right 2	left 1	left 2	steering 1	steering2	Right tire	left tire	steering	Ratio
90.14	91.52	90.19	88.85	111.81	148.48	-1.38	1.34	-36.67	26.96324
91.52	92.72	88.85	87.69	148.48	180	-1.2	1.16	-31.52	26.71186
92.72	94.44	87.69	86.05	180	134.78	-1.72	1.64	45.22	26.91667
94.44	97.7	86.05	83.02	134.78	51.06	-3.26	3.03	83.72	26.62003
97.7	99.73	83.02	81.18	51.06	0	-2.03	1.84	51.06	26.3876
99.73	103.22	81.18	78.1	0	85.35	-3.49	3.08	-85.35	25.98174
									26.59686

Table 15. Gear specifications used in tables 16 through 19

	new shaft gear	rack gear original	rack gear 2	rack gear 3	rack gear 4
teeth	10	16	22	38	30
bore	0.75	0.75	0.75	0.75	0.75
pitch	0.5	0.5	0.5	0.5	0.5
OD	1.84	2.81	3.78	6.33	5.06
DP	6.28	6.28	6.28	6.28	6.28
PD	1.59	2.54	3.52	6.05	4.77
		1.60	2.21	3.81	3

Table 16. Change in angle data for gear ratio 1.60

Ratio from gear to gear chain (1.60)						change in angle			
Right 1	Right 2	left 1	left 2	steering 1	steering2	Right tire	left tire	steering	Ratio
90.2	92.31	90.13	88.08	82.16	54.94	-2.11	2.05	27.22	13.08654
92.31	94.65	88.08	85.86	54.94	23.06	-2.34	2.22	31.88	13.98246
94.65	96.42	85.86	84.2	23.06	0	-1.77	1.66	23.06	13.44606
96.42	99.33	84.2	81.54	0	37.16	-2.91	2.66	-37.16	13.34291
99.33	102.88	81.54	78.39	37.16	81.27	-3.55	3.15	-44.11	13.16716
102.88	107.7	78.39	74.32	81.27	138.17	-4.82	4.07	-56.9	12.8009
									13.30434

Table 17. Change in angle data for gear ratio 2.21

Ratio from gear to gear chain (2.21)						change in angle			
Right 1	Right 2	Left 1	Left 2	steering 1	steering2	Right tire	Left tire	steering	Ratio
90.93	93.16	89.42	87.27	72.31	31.36	-2.23	2.15	40.95	18.69863
93.16	94.89	87.27	85.63	31.36	0	-1.73	1.64	31.36	18.61128
94.89	97.5	85.63	83.21	0	46.7	-2.61	2.42	-46.7	18.56859
97.5	101.53	83.21	79.58	46.7	116.95	-4.03	3.63	-70.25	18.34204
101.53	104.66	79.58	76.87	116.95	169.37	-3.13	2.71	-52.42	17.95205
									18.43452

Table 18. Change in angle data for gear ratio 3.81

Ratio from gear to gear chain (3.81)						change in angle			
Right 1	Right 2	left 1	left 2	steering 1	steering2	Right tire	left tire	steering	Ratio
90.28	93.24	90.05	87.19	48.47	142.44	-2.96	2.86	-93.97	32.2921
93.24	94.44	87.19	86.06	142.44	180	-1.2	1.13	-37.56	32.24034
94.44	96.51	86.06	84.12	180	115.79	-2.07	1.94	64.21	32.02494
96.51	98.71	84.12	82.1	115.79	48.46	-2.2	2.02	67.33	31.90995
98.71	100.33	82.1	80.64	48.46	0	-1.62	1.46	48.46	31.46753
100.33	102.72	80.64	78.53	0	70.46	-2.39	2.11	-70.46	31.31556
									31.87507

Table 19. Change in angle data for gear ratio 3.00

Ratio from gear to gear chain (3)						change in angle			
Right 1	Right 2	left 1	left 2	steering 1	steering2	Right tire	left tire	steering	Ratio
90.24	93.02	90.09	87.4	62.01	131.49	-2.78	2.69	-69.48	25.40402
93.02	94.99	87.4	85.54	131.49	180	-1.97	1.86	-48.51	25.33159
94.99	97.07	85.54	83.6	180	129.18	-2.08	1.94	50.82	25.28358
97.07	100.19	83.6	80.77	129.18	55.02	-3.12	2.83	74.16	24.92773
100.19	102.56	80.77	78.68	55.02	0	-2.37	2.09	55.02	24.67265
									25.12391

Appendix N - ABS MATLAB Model

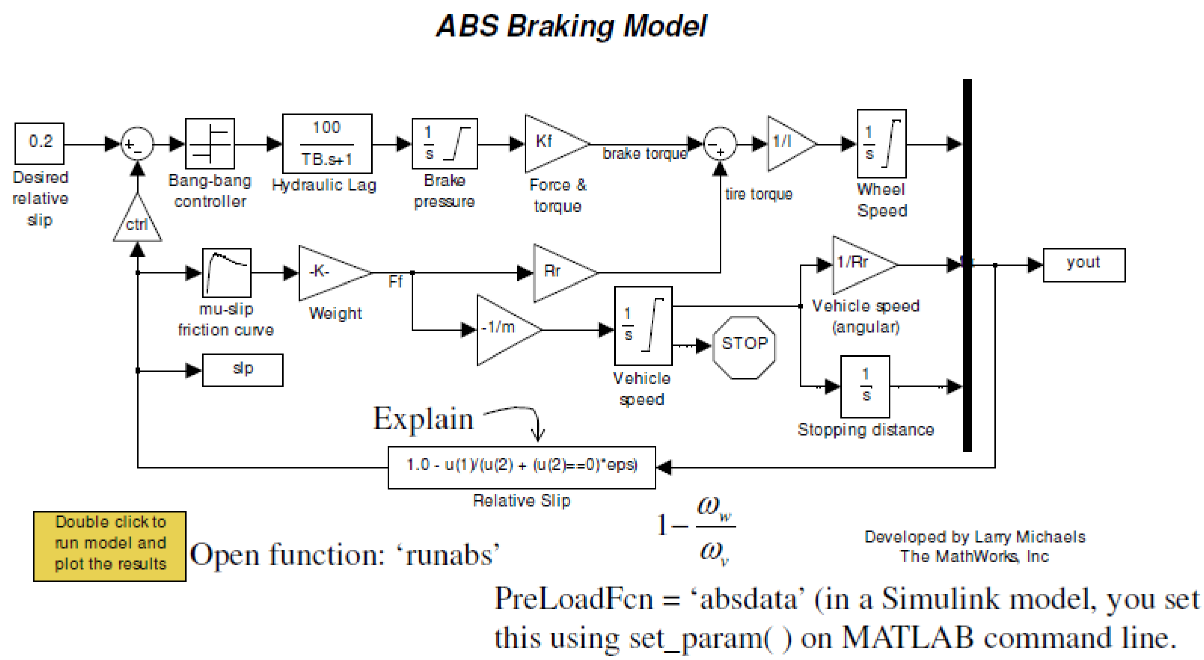

Figure 61 - This model is of one sensor and belongs to Professor R.G. Longoria of University of Texas at Austin.

Appendix O - Bump Steer

Bump steer is a phenomenon that occurs when one wheel of the steering system hits a bump and causes the opposite wheel to toe out. This occurs because the tie rods do not change length and the suspension is still constraining the wheels. This can be illustrated in the figure below.

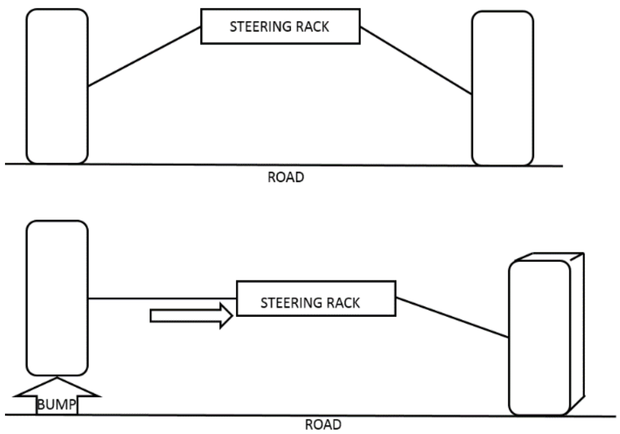

Figure 62. Bump steer effect

To mitigate this effect, the tie rods need to be adjusted so that they are parallel to the suspension. Thus, when a wheel gets a bump, the outside toe will be minimized as the suspension moves with the tie rod.

Eliminating bump steer completely requires having the suspension and tie rods aligned in such a way that lines from each of them can be drawn to a center point. This concept is illustrated in the figure below.

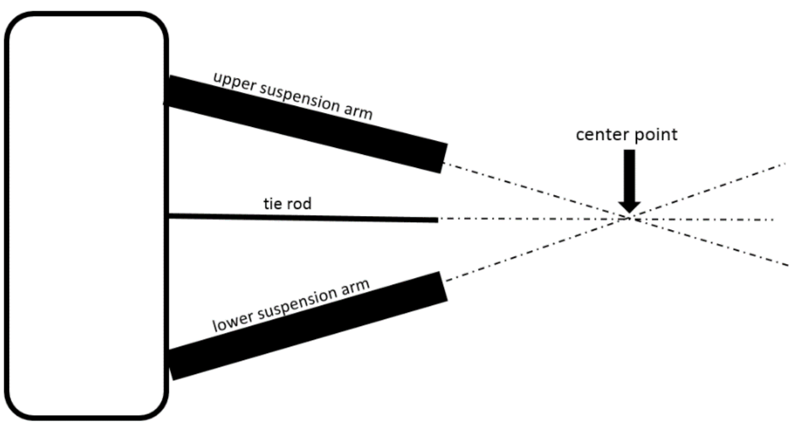

Figure 63. Elimination of bump steer

Appendix P - Using Autodesk Vault

Use of Autodesk vault is simple although it does not come across this way to the first time user.

Using Autodesk Vault starts by using the application it is being applied to (word, excel, inventor). The following will show the user how to start using the vault for a set of inventor drawings.

Login Information

To log in to the Vault, click the “Log In” button circled below in figure 58. The User Name is “Administrator”, the password is “”, and the server is “wireframe.calvin.edu”.

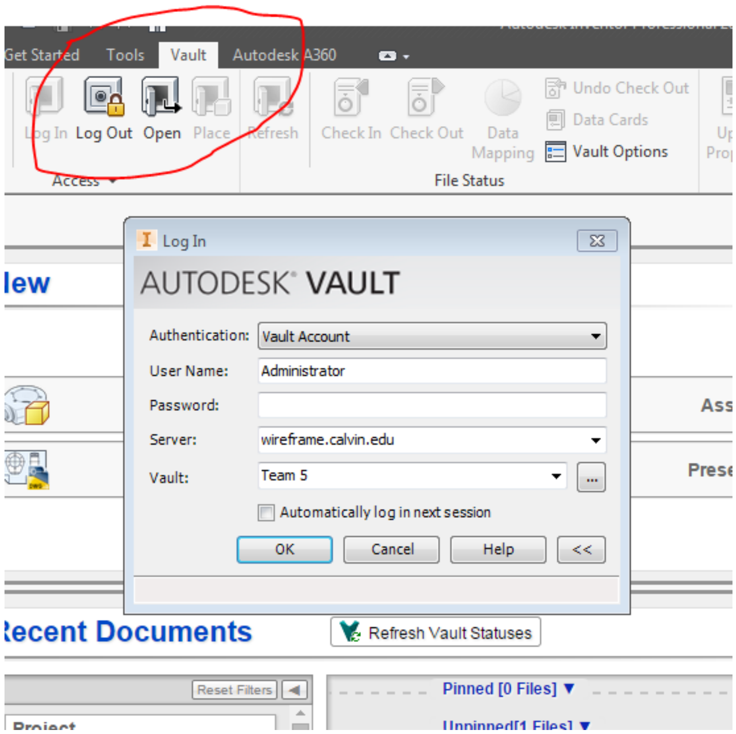

Figure 64. Logging in to the Vault from Autodesk Inventor

Create a New Project

Go to the get started tab, select projects. Upon reaching this dialog box, click “new”.

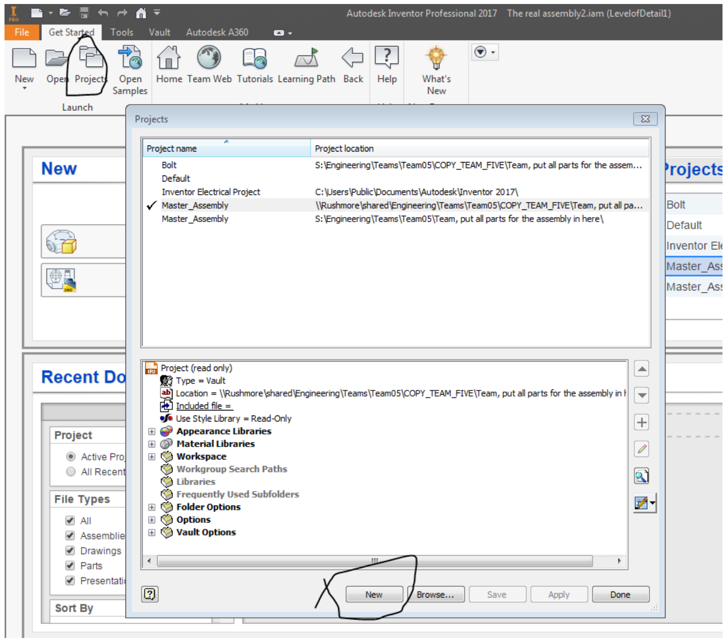

Figure 65. Creating a new project

Upon clicking new, select “New Vault Project” and click “next.”

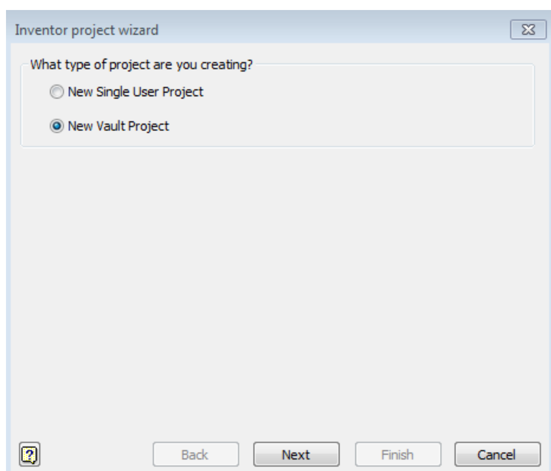

Figure 66. Creating a Vault project

It is important to make sure all of the design files being used are in one place. Give your project a title and select the folder where all your drawings are located. Click “finish.”

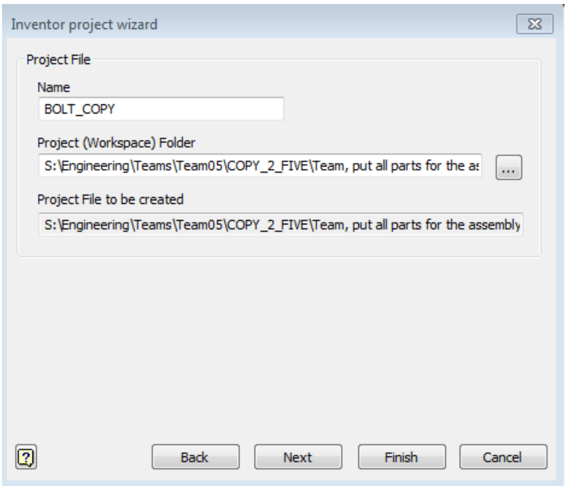

Figure 67. Giving your Vault project a name

Once the vault project has been created and the default file directory has been set, all the parts that have been created must first be checked into the vault. From here, the assemblies can be made.

Adding Parts to the Vault

When uploading a file to the vault directory, the workspace must be mapped to the vault folder that was created when the vault project was created. To do this, go to the vault tap and click "check in." The user will then receive a "check in error." Click "Map Folders."

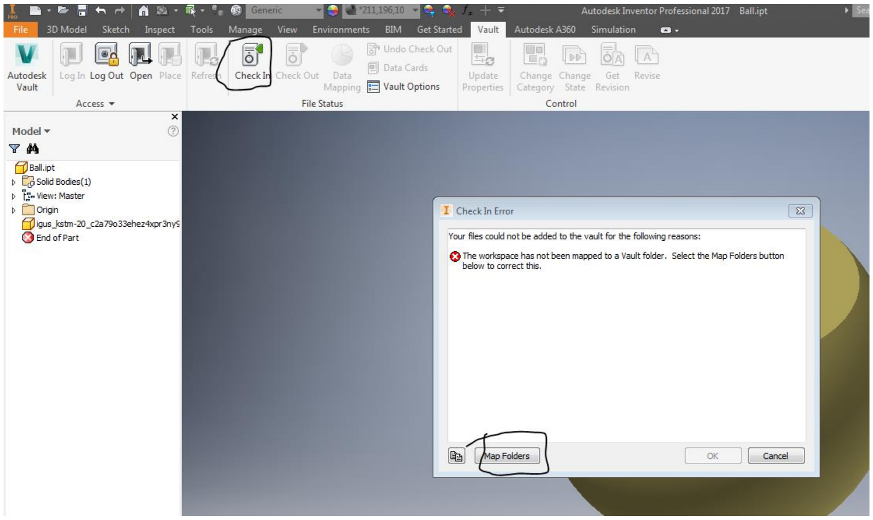

Figure 68. Checking a file into vault

Select "content center files" and select "edit."

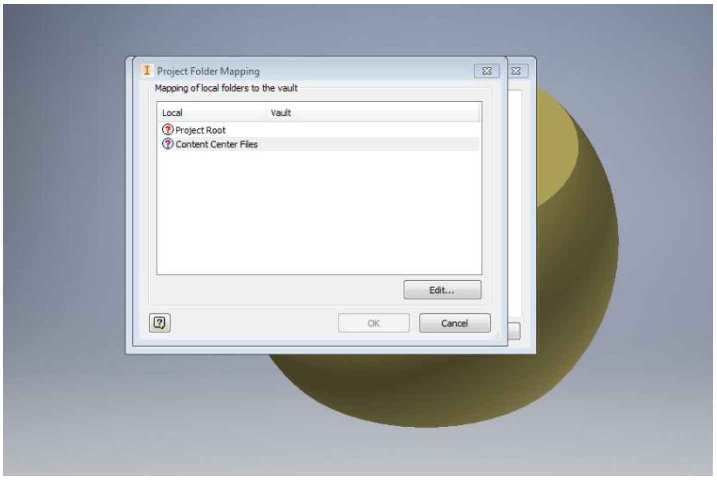

Figure 69. Mapping to the Vault directory

Next create a “New Folder” and be sure to click the “library” option.

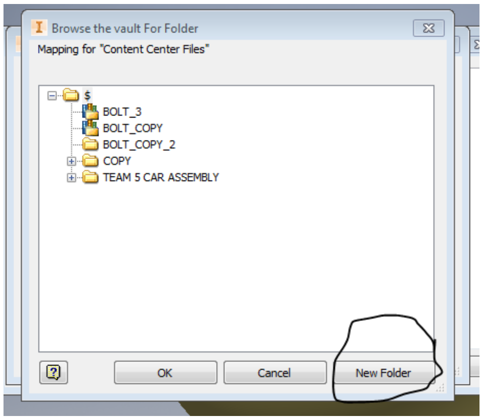

Figure 70. Creating the Vault folder

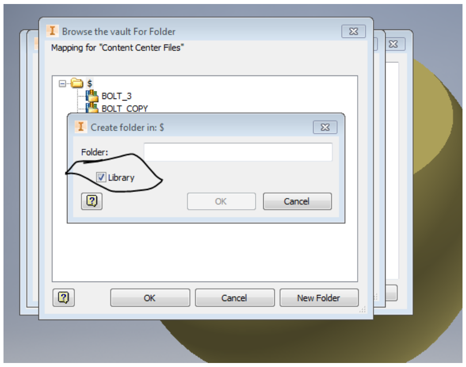

Figure 71. Creating a library

Once the library has been created, the part can now be mapped to the vault folder. Now whenever a part is opened in the default directory, one can simply click “check in” on the vault tab and vault will recognize the vault directory selected as the place to put cad files.

Creating Assemblies

It is recommended that assemblies are created from the vault and only after all the parts have been added to the vault. Once this has been done, create a new assembly. Make sure all the parts that were created and already checked into the vault are closed (no one has them open on any computer). If an error message appears saying the file is a "read only" file, it means the file is either checked in to another vault folder or is open by another user.

Upon creating the assembly, before adding any parts, "check in" the assembly. Once this is done, add the parts to the assembly. Be sure to frequently "check in" the assembly. This option uploads the assembly along with any changes made to it. This also saves the assembly. Once this has been done, be sure to "check out" the assembly.

Opening Files when Using Vault

Whenever one is using vault to document changes and the parts and assemblies have already been uploaded to vault, one must click the file tab, click the "open" dropdown menu, and click "open from vault." Simply opening the file that has already been uploaded to vault will open a "read only" file.

Other Resources

The engineering library as well as Bob DeKraker have access to a tutorial book on Autodesk Vault. The tutorial book is called "Autodesk Vault Professional 2017 (R1)." See pages 127 to 153 for more information.

Appendix Q - Data for Static Test on Braking System

Table 20. Estimated pulling force of the car varying number of passengers

Passenger (people)	F_skid (lbf)	
	concrete	asphalt
0	172.8	392.1
1	229.8	525.1
2	286.8	658.1
3	288.7	660
4	290.6	661.9

Passengers are ruled to take the front seats first, then the rear seats. Car with one passenger is when the Calvin Bolt is operating with the driver himself.

Table 21. Amount of pulling force improved with orinigal cylinder

Current System	
Force Applied	F_pull
40 lbm	210 lbf
70 lbm	310 lbf

Averaged values of test 3 in Figure 36 are recorded as shown in Table 21. From test 2 to test 3, braking force experienced 31.8% increase. Gradual brake force improvements, from test 1 to test 2, are listed in tables below:

Table 22. Initial test results (Figure 35: Test 1)

Force Applied (lbf)	
40	70
Force Pulled (lbf)	
79	170
86	185
85	154
84	198
98	265
98	193
65	170
76	210
85	270
79	190

Table 23. Initial condition with left hand side brake clamped

Force Applied (lbf)	
40	70
Force Pulled (lbf)	
60	88
65	102
66	121
66	65
65	79
70	77
85	50
74	74
66	84
74	92

Table 24. Initial condition with right hand side brake clamped

Force Applied (lbf)	
40	70
Force Pulled (lbf)	
45	88
65	102
44	121
62	65
56	79
82	77
60	50
65	74
81	84
45	92

Data in Table 23 and 24 may contain few outliers because noticeable wheel turn was occurred during the test. However, overall both the left and right brakes are relatively balanced as the force difference within 10% unbalance.

Table 25. Master cylinder in original pivot position (Test 2 in Figure 35)

Force Applied (lbf)	
40	70
Force Pulled (lbf)	
144	198
143	202
138	206
140	203
138	207
139	208
142	213
144	218
136	211
136	216

Table 26. Master cylinder in original pivot position (Test 2 in Figure 35)

Force Applied (lbf)	
40	70
Force Pulled (lbf)	
163	211
179	214
169	212
159	202
156	186
166	188
145	188
156	176
156	188
165	186

Compared to the data in Table 25, brake force had an increase of 17.8% after pivot point was elevated. In Table 26, braking force (pulling force) was dropped from 210's to 180's due to the leakage of brake fluids through calipers.

Appendix R – Brake Lever Arm Analysis

Table 27. Pulling force change by brake lever arm modification (only elevation, dY)

Lever Modification (dX =0 in)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40 lbf	232.848	255.486	278.124	300.839
70 lbf	341.25	374.79	408.265	441.74

Table 28. Pulling force change by brake lever arm modification (1 inch is added horizontally, dX)

Lever Modification (dX =1)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40	251.02	273.812	296.527	319.165
70	368.42	401.895	435.37	468.845

Table 29. Pulling force change by brake lever arm modification (1.5 inch is added horizontally, dX)

Lever Modification (dX =1.5)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40	260.337	283.052	305.69	328.328
70	382.005	415.48	448.89	482.365

Table 30. Pulling force change by brake lever arm modification (2 inch is added horizontally, dX)

Lever Modification (dX =2)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40	269.5	291.83	314.853	337.491
70	395.525	429	462.475	495.95

Table 31. Pulling force change by brake lever arm modification (3 inch is added horizontally, dX)

Lever Modification (dX =3)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40	287.903	310.541	**333.179**	355.817
70	422.5	455.65	**489.45**	523.055

Table 32. Pulling force change by brake lever arm modification (4 inch is added horizontally, dX)

Lever Modification (dX =4)				
Force Applied	dY = 1 in	dY = 2 in	dY = 3 in	dY = 4 in
40	306.229	328.867	351.505	374.143
70	449.735	483.21	516.685	550.095

'dY' refers to the length added in vertical axis. 'dX' refer to the length added in horizontal axis. In dimension wise, the longer the better, but 3 by 3 (bolded) inches provided more comfort in seats than any size greater than that.

Appendix S – Parking Pedal Lever Dimensions

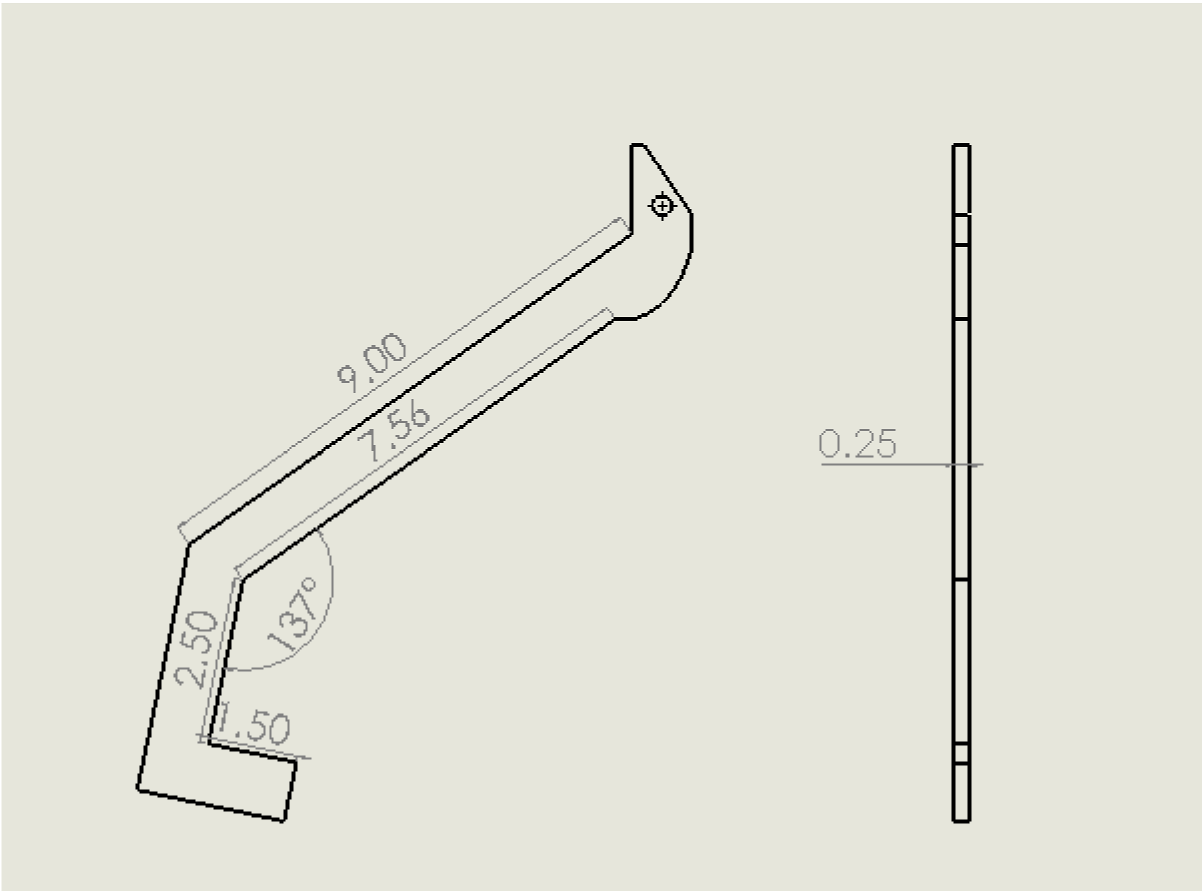

Figure 72. 2D drawing of parking brake pedal

Units are written in inches in Figure 72. Designed dimensions may differ from the reality due to the measuring tolerances and manufacturing process.

Appendix T – Accessing the Team Share Drive & Backup

Accessing the CAD Files

The main assembly file used by team five was called “The real Assembly2.ipm”. Its location would have been found under:

Team05\COPY_TEAM_FIVE\Team, put all parts for the assembly in here\THE REAL ASSEMBLY ASSEMBLY

“Team, put all parts for the assembly in here” is where the vault folder is also located. Remember to log in to the vault first before accessing the file. See appendix P for details on using Vault.

Team Contact Information

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