Calvin Bolt: Steering and Braking Optimization

Team 5

Calvin Bolt 3.0

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Engr339/340 Senior Design Project

Calvin College

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Executive Summary

Calvin College's engineering curriculum require a design project to be done in the senior year. Throughout this year, a team of students designs something while incorporating design norms and the Christian faith, for these values will be carried in to the work force.

Team five is working on a project that has been attempted by previous groups before them. The goal was to build a vehicle that could transport people around the campus, while also being an icon for the Engineering program at Calvin. Unlike the previous groups before them who attempted to build an entire vehicle inside a year, team five will work off the previous Calvin Bolt vehicle and focus on enhancing only the braking and steering system. By only focusing on these aspects they will be able design these mechanisms better with the time given to them. Furthermore, they will use a version-control software to make it easier for future teams to work on different aspects of the Calvin Bolt to eventually make it a proud symbol for the Calvin College Engineering Department.

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1 Introduction

When an engineering prospective 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 1.1 - Team Picture; from left to right, 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. He participates in college cross country & track. He also participates in Army ROTC and is hoping to pursue a military career after college. For the past ten years, he has been involved with Pine Bush Bible Camp, a summer camp dedicated to telling young kids about Jesus.

Over the past few summers, he served as camp program director, archery instructor, as well as handling the camp morning devotions. He is looking forward to continuing his support of Pine Bush Bible Camp after he graduates along with getting ready to run his first marathon.

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 boat 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 different cultures around the world. Upon graduation, Bernice hopes to 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 inspiring more women to take an interest in Engineering.

1.4 Project Overview

1.4.1 Previous Groups

Previous groups before have tried to design and manufacture an entire vehicle in less than a year. In a sense, they succeeded in their goal but with their limited time and large goals they were not able to design the components of the vehicle properly. Team five's goal 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 be focusing on designing the braking and 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.

1.4.2 Braking System

Figure 1.2 - Disk Brake of the Calvin Bolt

As shown in Figure 1, the previous design team installed the current disk braking system with hydraulic fluid on the Calvin Bolt. Not only did they want to follow the common trend of cars today, by having a disc braking system over a drum braking system, but they also reused parts from the older design team's car, the Volts Wagon, to save money within their budget. However, based on our inspection and test drive, the Calvin Bolt's braking system did not provide enough force, the pressure provided from the master cylinder to the disc calipers by means of the hydraulic fluid, to stop the car when desired; instead, when the brakes are pressed, the vehicle extends its distance before coming to a complete stop.

Figure 1.3 – Parking Brake of the Calvin Bolt

In addition, as shown in Figure 2, the parking brake of the vehicle was poorly designed in that the parking brake lever did not effectively lock the braking pedal. For this reason, team's goal on 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 and to re-designed the parking lever to be suitable for the new frame of the car. In addition, to increase driver and passenger safety, Anti-Lock Braking system (ABS) will be designed into the system to prevent skidding.

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.

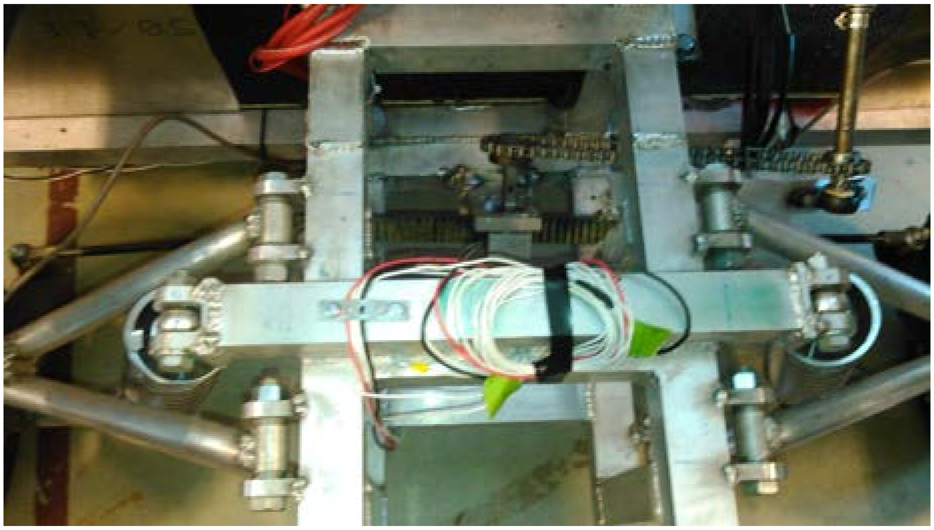


Figure 1.4 – Overhead picture of the old steering system

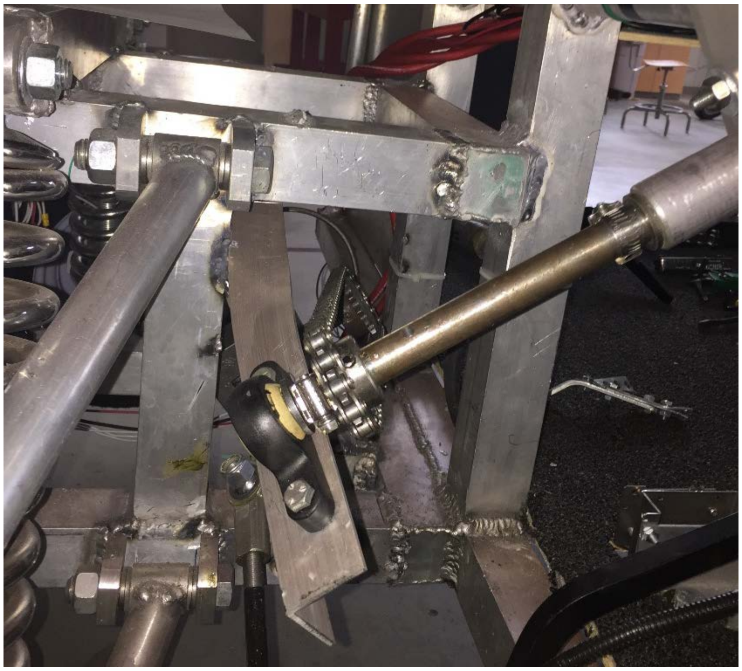


Figure 1.5 – Side view picture of the old steering system

The goal is to design a power steering system that will make it easy 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 eliminate the gear component completely by having the shaft directly connect to a newly designed rack and pinion system which will them give the steering shaft more stability as well as slightly decrease the force needed by the driver.

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. With this in mind, 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 in order for future teams 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 it could learn as they go through its design process.

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 2.0, the department decided to keep the vehicle, however with no concrete plans for it. Therefore, after speaking with Professor Nielsen about the decision to keep the vehicle along with its history, we 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.

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 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 be so amazing that like the temple, it will attract perspective students from all across 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, which the car contains, and requested to improve its current design as effective as possible. This led team five to conduct 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, is 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 is not 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 for the vehicle to stop completely. For this reason, the team related the core problem to the brake mechanism's efficiency and devised to install an Antilock Brake System (ABS) on the disc brakes as an improvement to the overall system. In addition, to ensure functionality and reliability, team five will be required to replace any components that do not meet good standing in their own service conditions based on several car repair manuals.

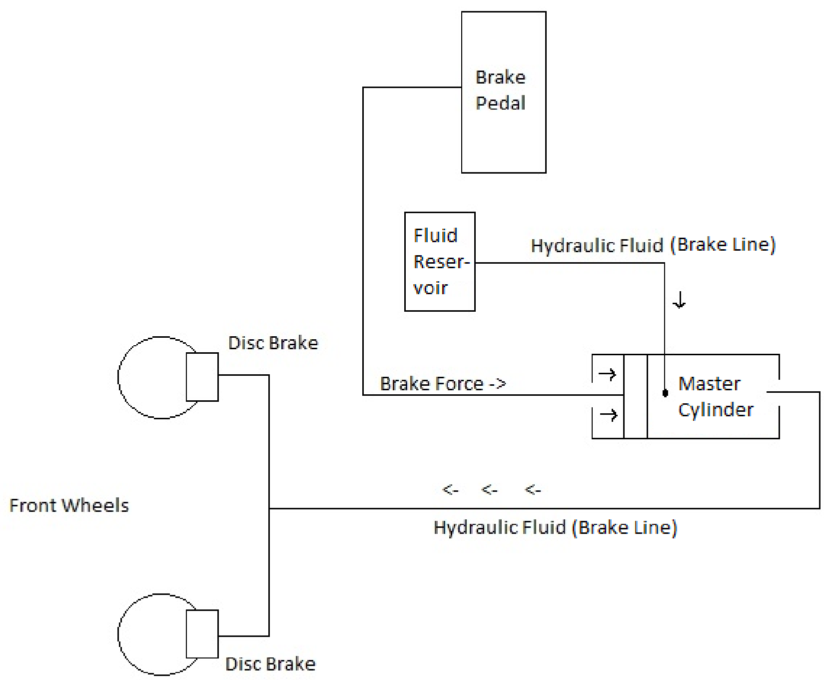


Figure 2.1 Braking mechanism of the Calvin Bolt

However, on the other side of the project scope, team five will be required to keep their approved budget at or below $500. Price estimate on each component of the entire braking mechanism is not fully covered and will require additional funding. To limit total expenditure, team five thought that it will be wise not to design with huge changes to the original mechanism. Thus, for the first and second requirement, team five decided to keep the same hydraulic disc braking mechanism as shown in Figure 2.1 and to save as many parts as possible from the Calvin Bolt. Then, based on repair manuals and necessary calculations, team five will decided which parts in the braking system must be replaced to cause a complete stop directly, satisfying its velocity specification (25 mph max.).

Thirdly, for ABS system, 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. Meanwhile, team five will also consider the car's weight balance when undertaking manufacturing processes in Spring.

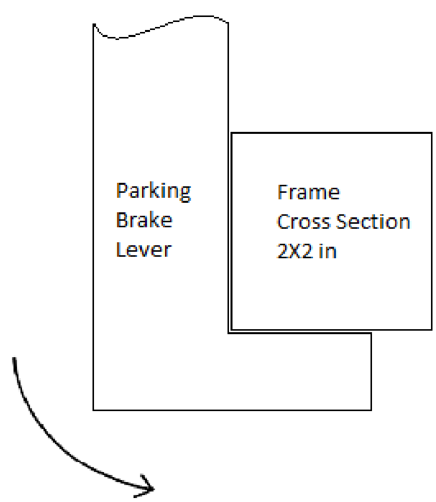


Figure 2.2 - Re-design of the Parking Brake Lever with its own principle.

Re-designing the parking brake lever is the last requirement for our senior design project. Since the previous team directly imported the brake pedal from a used golf cart, the parking brake that is currently installed is not lock the brakes efficiently for the Calvin Bolt. For making the parking brake operable, team five will consider improved angle of rotation and dimension so that the parking pedal completely lock up the brake pedal at 2 x 2 inch across section. 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 inclined.

2.2 Steering System

Team five will be designing a power steering system which will be used to assist the driver when turning. Electronic power assisted steering was found to be the best option. In an electronic power assisted steering system consists of a rack-and-pinion system attached to an electric motor, and a torque sensor attached to the steering shaft as shown below in Figure 4.

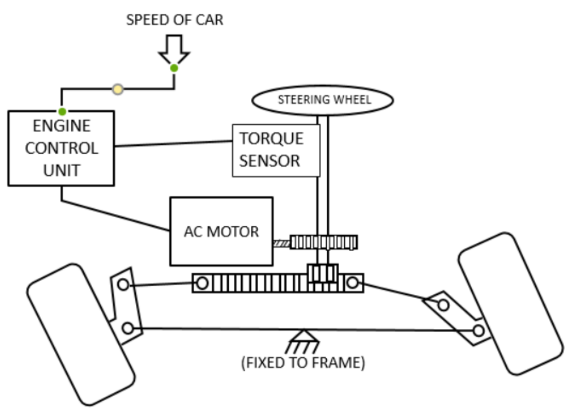


Figure 2.3 – Diagram of an electronic power assisted steering system

A power steering system works the same way but adds an A/C motor and a torque sensor. In a simple power steering system, the AC motor is attached to a screw which is meshed with another gear. This gear is attached to the steering wheel shaft. The torque sensor then senses how much torque the driver is applying and tells the AC motor to spin through a control system. This provides an assist to the driver.

The control system must be designed properly in order to assist the driver safely. Not only must the control system respond to the torque exerted by the steering wheel, it must also respond to the speed of the car. If the AC motor provides too much of an assist at high speed, such a turn could cause the car to flip over and cause damage to the driver. See Appendix A for more information. The control system will need to be designed based on the mechanical design of the steering system so we will need to get that done as soon as possible to leave room for the design and adjustment of the control system.

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. See Appendix B for force calculations.

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.

Steering Requirements:
By estimating the center of mass, the car must not be allowed to make a sharper turn than, therefore and added sensor for the angle of the wheels may be necessary as another input to the engine control unit.

Avoiding Roll Over:
The power steering system must be designed to prevent roll over. Assuming the center of mass of the car to be at a height of .6 meters +-.2 meters, the center of mass being at ½ width at .8 meters +-.1 meters, a max speed of the car of 20mph +-3mph, the tightest turn the car would be able to make on a level road would be 17 meters with an uncertainty of +-3 meters.

Turn Radius of the Car:
The turn radius of the car is 3.5 meters with an uncertainty of +-.5 meters. The power steering system must be capable of turning the car this far. See Appendix H for more information.

Power Required to Turn the Car:
The power required for the power steering system is around 2000kW. See Appendix I for more information.

Response Time to make a Turn:
The power steering system must have response time of less than 10ms. (Frank, 2006)

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 5 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 Time Feasibility

The design and improvement upon the steering and braking system, along with the final update of the Version Control software must be completed before or on May 6th, 2017.

2.5 Budget

All improvements will meet the $500 budget approved by the Calvin College Engineering Department. Additional funds can be included upon requests and donations, etc. In terms of integrity, the team should be upright for any budget for the design as much as possible.

2.6 Project Deliverables

The Calvin Bolt 3.0 team will complete a Project Proposal and Feasibility Study (PPFS) and a Final Report. Team five's completion will include all drawings, relevant calculations, log book, 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, and the team also recognized the need of establishing combined database for prospective seniors for the future. The Breakdown of the two technical systems will focus on how team five approaches to the manufacturing process of prototype.

3.1.1 Braking System

The Calvin Bolt is designed as a hybrid between a golf cart and a modern vehicle (Boluyt, DeVries, De Zeeuw, & Rovedatti, 2016). The previous team of the Calvin Bolt devised the braking mechanism from a general car, whereas they installed a different brake kit for their vehicle. The previous team used parts that may not withstand at the vehicle's desired speed at 25 mph. According to the ANSI standard for golf carts production (American National Standards Institute, 2012), all devices in the transportation must be designed to support the speed that is less than 15 mph. For this reason, major research and developing alternatives on braking system will be accomplished based on the service inspection of the components that currently exist on the braking assembly.

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

Braking pad – The main friction 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. 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, selecting the right material and thickness for the pads allow the brake assembly to resist temperature increase and wear. Thus, the pad material should be capable to withstand heat and wear.

Disc – The disc (rotor) is the simplest components in the braking system. In braking assembly, the disc is the part where the brake pads obtain their desired brake force from its rotational momentum. Wear on the brake disc is caused by the brake pads, and team five needs to inspect its current condition of service. Thickness variation will be measured on several different spots on each rotor. Disc's runout will be also checked for corrosion on the lug nut and uneven torque applied when being reassembled.

Caliper – The brake calipers are the device that supports the braking pad clip the rotor. Using a hydraulic piston. Caliper's piston helps to transmit hydraulic pressure through the hydraulic lines from the brake pedal. Team 5 will inspect whether the current defect on the braking mechanism is related to caliper pistons (master 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 will carefully consider its lever's geometry with the angle rotation of both the brake pedal and parking pedal itself.

ABS - This is also known as Anti-Lock Braking System. The device was designed to prevent skidding of a vehicle while kinetic energy of the car is preserved. Hydraulic fluid of each side of the brake apply an equal amount of pressure on the brake pad, and it causes uncontrollability of the steering wheel. Thus, team 5 will ultimately attach an ABS sensor on each of our brakes to redistribute the pressure on left and right wheels. Although ABS and power steering both require an electronic control unit (ECU) to operate, the final decision as to whether both will have a combined ECU or separate ECU's will be determined in Spring due to lack of current funds as well as in-depth research comparing possible consequences involving two separate systems on one common ECU.

3.1.2 Steering System

The main components of the steering system are the AC motor attached to the driving shaft and the control system which is attached to a torque sensor and the car motor. Phase one is designing the mechanical structure of the steering system. It has to be design so that the electronic components of electronic power assisted steering system can be easily implemented. Phase two begins with the design and implementation of the control system. During this phase, testing and adjustment of the control system will occur to make sure that the correct amount of assist is being applied to the steering shaft from the A/C motor.

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 Schedule

The schedule for next semester can be reviewed in Appendix C.

3.3 Team Roles and Responsibilities

Philip Kim volunteered to take minutes during each of our team meetings. Nathan put together the team schedule and helped make sure the team was making its deadlines. Philip took the lead role on breaks while Sam took the lead on the control systems. Bernice took the lead on documentation software and implementing it early into the design process.

4 Design Analysis

4.1 Initial Analysis

Team fives initial diagnostics of the car and what was told to them by professors that helped with making it last year showed that it fell up short in many ways to what the customer wanted from the project. Although there were many aspects that team five thought they could work on they did not want to make the same mistake that the previous group did and attempt to bite off more than they can chew. Instead 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 is 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 makes it an excellent design option for making adjustments. No fluids also a cleaner system with less maintenance required. No lubrication is required.

The Electronic Power Steering system will require a control system to be designed. The control system will 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 4.1 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 4.1 as well.

Table 4.1 - The effect of increasing one of the parameters independently (found on Wikipedia, url in Work Cited section)

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

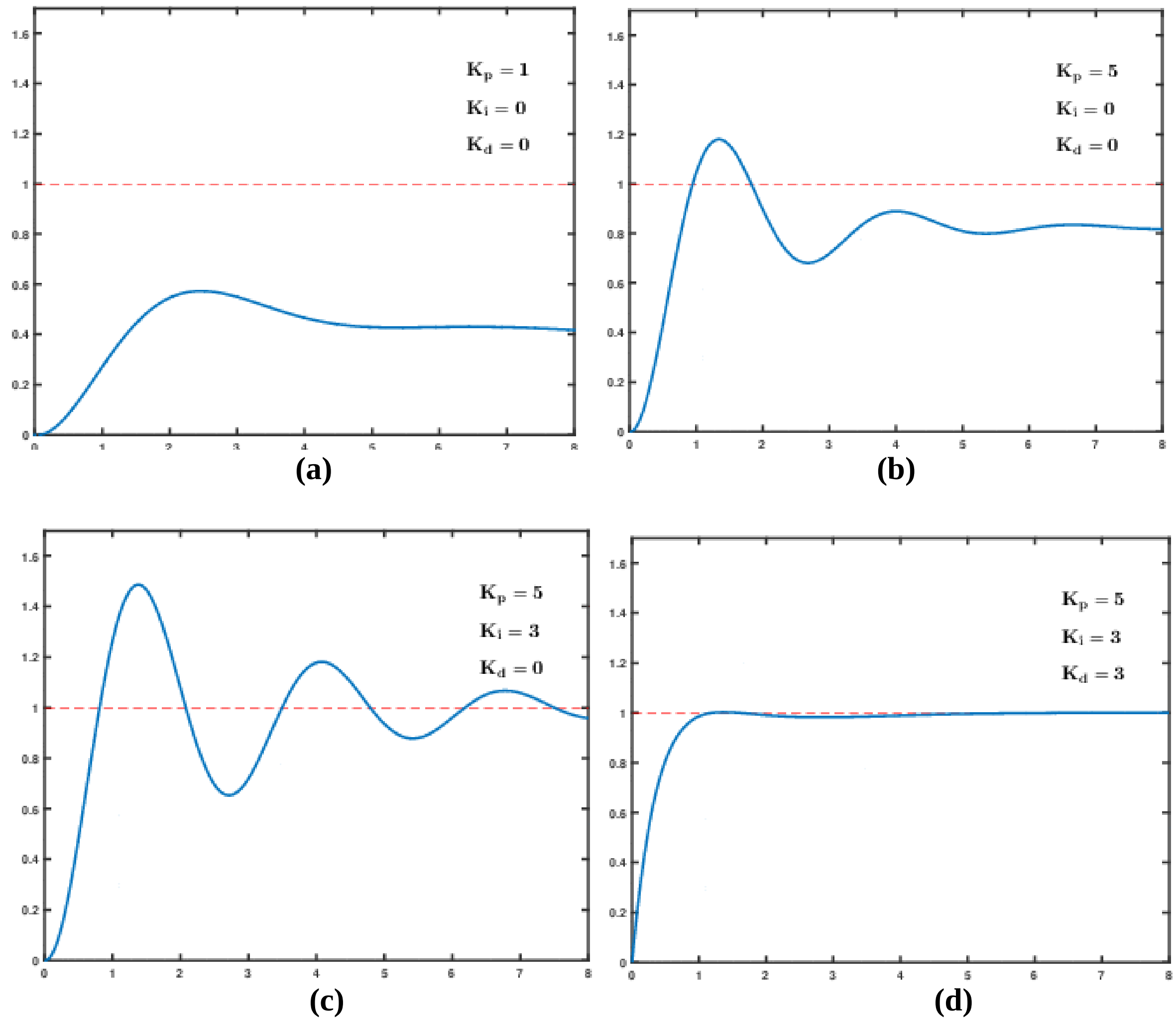


Figure 4.1 - Step response plots with time (sec) on the x-axis and amplitude on the y-axis showing the effect of a PID controller when, (a) No parameters are added, (b) the P parameter is amplified, (c) the I parameter is added and amplified, and (d) the D parameter is added and amplified (found on Wikipedia, url in Work Cited section)

4.2.2 Alternatives

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

Rack-and-pinion is the current design and requires 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. Such a design would reduce the torque required by the driver but would lack the aesthetics needed to be displayed in this project. Although a practical solution, it does not add anything interesting to the car itself, which is important if this car is to be used to attract perspective students.

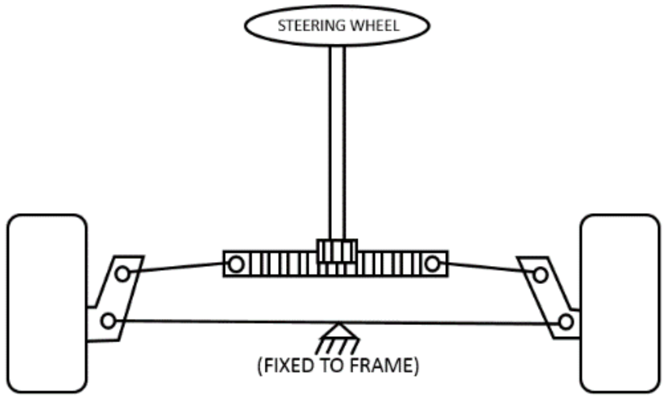


Figure 4.2 Simple rack-and-pinion steering system

The hydraulic system has one advantage over the electronic option which is that it does not require an AC motor. The hydraulic system however would require a compressor which in this case becomes an unneeded extra component for this project.

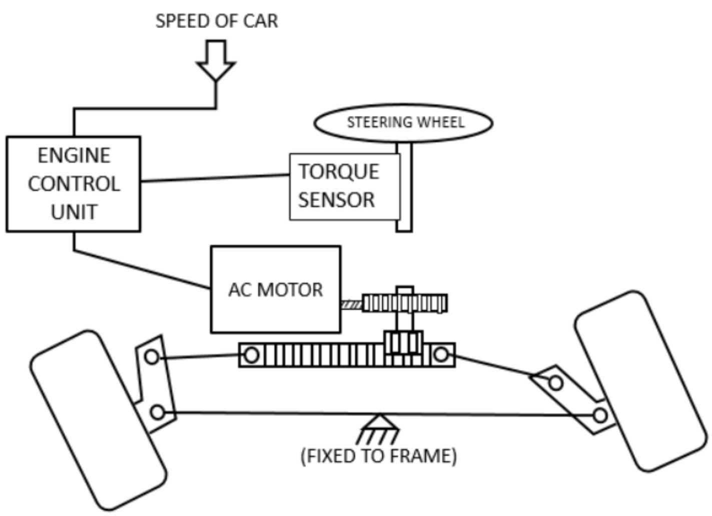


Figure 4.3 – Diagram of a joystick configuration of an electronic power assisted steering system.

4.2.3 Decisions

In the end while considering all of the alternatives based on efficiency, cost, and variability, team five decided to design an electronic power assisted steering system. This is the best design for both functionality and variability in consideration for the work that future design teams will do.

4.2.4 Implementation

After the initial designs in AutoCAD and the calculations for the system team five will then begin to make prototypes separate from the car to see the functionality of the system being designed. After a number of prototypes, we will them make a final one that we will then put into the car. The implementation of the control system will be the most difficult and least feasible part of this project based on cost and design requirements. When communicating with Professor Kim he informed team five that the control system may be outside the scope of this project based on time and complexity. Therefore, a model of previous research done by someone else should be found to cut down on time for designing and implementing the control system.

4.3 Braking System

Team five has inspected every item involved in the braking assembly to understand main cause for the car why it does not stop completely. Overall, the decision on the final suggestion was focused on the re-use of items and the alternatives are only mentioned when a replacement is required.

4.3.1 Research and alternatives

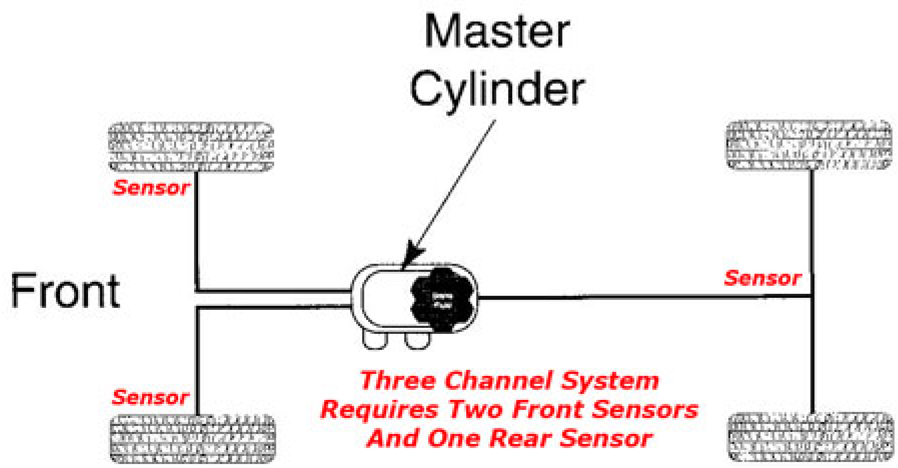
Braking pad - Disc braking assembly becomes fully functional when the braking pads provide enough thickness (Gilles, 2012). As braking pads have much wear beyond their allowable standard, the disc brake itself not only provide adequate friction to the car, but also it negatively affects the function of related items, such as the rotor. The minimum thickness of the pads varies depending on the material used and the shape it is designed. According to the service manual that team five has, the brake pads must be replaced when the thickness reaches 0.125-.1875 inch. The pad thickness of the Calvin Bolt was 0.14 inch. Team five also observed uneven wear on the pad, but we confirmed that the degree is not critical (0.0005 inch) as the manual states (less than 1/8 inch).

Disc - Inspection on the disc (rotor) was performed in three different criteria: general thickness, thickness variation, and runout existence (Gilles, 2012). As a result, the disc provides enough thickness and thickness variation according to the inspection manual. For the runout existence, it will be checked once the actual design is constructed in spring. Thus, the brake rotor does not need to be replaced. See Appendix E for rotor inspection results.

Caliper - Visual inspection on the brake calipers did not require much processes. Since the disc assembly was brand new, team five did not find/notice any crack, noise, or significant leaking from its piston (Gilles, 2012). However, based on the pressure calculation by pascal's law, team five appreciated why the brake mechanism would not fully provide friction to stop the car. Since the brake mechanism is missing another component that amplifies braking pressure to the braking piston, even though the fluid is fed, the pressure applied by the pad is much low. See Appendix F for hydraulic force calculation.

Parking Brake - Given that our budget is limited, team five decided to re-design the parking brake instead of purchasing another one. Firstly, team five detached the parking lever from the brake pedal and studied the geometry how many parts the pedal is consisted of. Then, measured every dimension 1/8 inch and 1 degree of tolerance, respectively. For the new design of the lever, since the team must ensure complete lock-up, new geometry of the lever was considered two rotational angle: rotation of the parking pedal itself and the brake pedals pressing angle. In material wise, team five checked the availability of the metal shop in light of various metals that can be used and how we can shape the work part as desired by our parking lever drawing. Aluminum (6061) and Steel (1008 or 1010) remained as the three options, and the use of computer numeric control (CNC) machine was selected to shape every component; then weld them into one piece.

ABS – Although 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, Figure X, which takes into account the rear axle and the front two wheels (a three-channel ABS) (Nice 2000).



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

Figure 4.4 - Basic outline of a three channel ABS system.

4.3.2 Decisions

Braking pad - Team five concluded that the brake pads are not appropriate for the vehicle and concluded to replace it into thicker pads because the thickness of the pad has reached the intolerable range for pad thicknesses. For pad's materials, ceramic, metallic, and organic pads are currently being considered, and the final decision will be made in spring. See Appendix G for material properties.

Caliper - Team five decided to include a bigger cylinder, such as brake booster, to amplify braking pressure from the pedal pressing. As there is a need for replacing it into the two piston caliper, wider cross section of brake pad is considered. Installing brake booster is also recommended for the pressure amplification. However, these two issues have to collaborate with the ABS system that will be set up on the brake kit.

Parking Brake – In regards to the type of material, team five decided to use steel because of its popularity and better strength than other materials. For specifics, as to which brakes will be implemented exactly, the final decision will be made in early spring. See Appendix G for material properties.

ABS – Although the first applications are most commonly used in vehicles, both options would allow team five to purchase, design and implement two additional braking systems for the rear wheels which would cause multiple conflicts. Some of these conflicts include adding additional weight to the back of the vehicle (which is already heavier than most vehicles) and would significantly reach beyond our budget. Because team five wants to keep and reuse as much of the current vehicle as possible, the three-channel ABS alternative is chosen.

4.3.3 Implementation

New parts will be purchased and developed into the current braking system. The braking system will be tested once the initial prototype is made upon material selection. More thorough calculation, such as heat dissipation of the pedal, will need to be performed to achieve a better adjustment; this is scheduled to be completed in the spring. Depending on the vehicle's performance through the test, the braking system will be updated with additional modification based on the goals for our requirement.

As for ABS, research will be narrowed down from various ABS systems to the necessary steps and requirements of implementing a three-channel ABS. In addition, further investigation will be conducted in the Spring to determine whether or not the ECU for the ABS will be combined with the power steering. Although implementing a combined module is possible, there exist the risk of the ECU malfunctioning causing both the steering system and braking system to become impaired. However, if a combined ECU is implemented, the cost is lowered, but so is the safety of all aboard the vehicle. Likewise, if separate ECUs are implemented, although the cost rises, so does the safety of all inside the vehicle. With two important risk factors to consider, further discussion and research will be conducted with a final decision in the Spring. The ABS testing will be tested and simulated using the computer software MATLAB.

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. In the end, the chosen version control software will depend on the specific project and demands a company or in our case, a team, seeks.

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 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.

Incorporating a central flash drive that will contain all the raw data files developed throughout the design process allows team five to not only lower the cost, but keep the data of students whose Calvin account is no longer active available. The raw data files will vary from email exchanges, CAD files, word documentations, and other files involved in the design process. The Engineering Department will keep ahold of the flash drive and pass it down to the next senior design group that will be designing improvements on the vehicle. Team five feels this alternative will provide a nostalgic connection between the groups of the past and future.

4.4.3 Decisions

Taking into the considerations of cost, usability, and variability, Synergis is the chosen version control software team five will be implemented into their project. Although the other alternative was available at no cost, there were a lot more limitations than Synergis. In addition, the alternative appeared to need some C language coding and with team members that all lack proficient skills in C language, choosing the alternative would have turned out to be a nuisance rather than a form of aid.

4.4.4 Implementation

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 CAD drawings between team members. This will allow the team as a whole to keep a record correlation of specific changes to the team member who made the change.

5 Business Plan

5.1 Market

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

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

Team fives chief competitors will be 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. (Annual Report 2015)

CooperStandard is also a Michigan car parts company which specializes in braking systems. Last year CooperStandard did 32. 7 million dollars' worth of business. (Hardt, 2016)

Both of these 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 will 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. (List of Chevrolet vehicles, n.d.)
3. Lastly, team five will place an emphasis on online availability. A design guide will be placed on the team website which can be viewed for a small price. This guide will be used to target hobbyists who are enthusiasts in car design.
4. Team five will take advantage of online advertising. A short two-minute video advertising the product will be placed online.

Estimated Costs of Production

See Appendix D for summary of cost. Team five estimates that a full steering and breaking system can be assembled in ten days. 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.

Nexteer is a world class supplier of power steering systems.

Since team five is designing a braking and steering system for a vehicle the market is not centered around the production of the electric vehicle but only the components that they are being designing in this project. Therefore, the market that they are targeting for this project will be automobile companies that would buy their steering and braking.

5.2 Cost Estimate

The costs for the materials to build the braking and steering assemblies will be researched and will be found in a table, as shown below. The team estimated whether the sum of all individual components will meet the budget less than or equal to $500. Main source of each component will be found at used car market.

Table 5.1 – Cost estimate for components needed for project

Cost Estimate	UNITS	PRICE	TOTAL	STORE
Version Control Software	4	$0.00	$0.00	
AC motor	1	$400.00	$400.00	McMaster Carr
Torque Sensor	1	$300.00	$300.00	
Angular wheel sensors	2	$200.00	$400.00	
Engine control unit	1	$150.00	150.00 $	
Wire 1mm thick (ft)	30	$0.05	$1.50	
Electric Actuators	2	$5.00	$10.00	
Hydraulic Seal (trip to mechanic)	1	$70.00	$70.00	
Worm gear+ screw thread	1	$75.00	$75.00	
New Drive shaft	1	$200.00	$200.00	
Scrap metal	1	$100.00	$100.00	
Braking Pads	2	$30.00	$60.00	Carparts.com
Caliper	2	$40.00	$80.00	Carparts.com
Brake Booster	1	$100.00	$100.00	Carparts.com
Parking Brake	1	$0.00	$0.00	Calvin Metal Shop
Wheel Speed Sensor	3	$190.00	$480.00	Repair Pal
ABS Control Module	1	$120.00	$120.00	AutoZone
ABS Solenoid Valve Kit	2	$90.00	$180.00	Amazon
ABS Pump/Motor	1	$470.00	$470.00	AutoZone
Total			$3,046.50	

6 Conclusion

6.1 Evaluation

Team five has found the Calvin Bolt 3.0 senior design project feasible. 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 will allow for projected focus on the two systems thus resulting in highly reliable and functional systems. In addition, focusing on two systems (in addition to the version control software) makes team five susceptible to completing the design on time adding to the design's overall feasibility. 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.

6.2 Future Plans

In the following months to come leading up to senior design day, team five will begin building prototypes for the systems as the continue to revise their design with each prototype to then final have a braking and steering system that they will install into the vehicle. While these steps are being taken they will be sure to document their process and results as much as possible to ad in the transparency for future design teams who work on this car.

7 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.

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Professor Jeremy VanAntwerp – Team Advisor

Professor Ren Tubergen – Mechanical design consultant

Professor Yoon Kim – Control system consultant

Troy M. Kinne – Industrial consultant

Phil Jasperse – Metal shop supervisor

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9 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. (Hyperphysics, n.d.)

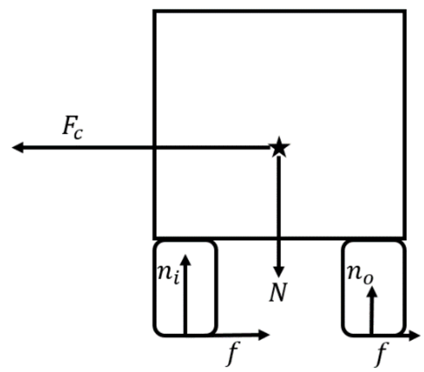

Figure 9.1 – Diagram showing the forces that are exerted on a vehicle as it turns

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

$$\sum F_x = 0 \qquad \sum F_y = 0$$

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

$$n_i + n_o = N$$

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. (Roper, 2001)

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]

$height_{of,cg}$ = 0.7 [m]

s = 0.7

$turn_{radius}$ = 2 [m]

v_{crit} = 8.941 [m/s]

y = 0.7

g = 9.81 [m/s^2]

r = 11.64 [m]

SSF = 0.7

v = 20 [mph]

x = 0.5

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 9.1 – Schedule for future plans and deadlines

Week	Dates			Calendar	Project Deadlines
-6	13-Nov	-	19-Nov		Rough draft PPFS completed
-5	20-Nov	-	26-Nov	Thanksgiving	Control system Research
-4	27-Nov	-	3-Dec		Bill of materials estimation
-3	4-Dec	-	10-Dec		Electrical Power Assisted Steering concept completes
-2	11-Dec	-	12-Dec		Breaking system concept completed PPFS completed and edited
-1	18-Dec	-	24-Dec	Christmas	PPFS turned in
0	25-Dec	-	31-Dec	Christmas	
1	1-Jan	-	7-Jan	First week Interim	CAD design of steering system
2	8-Jan	-	14-Jan		CAD design of breaking system
3	15-Jan	-	21-Jan		
4	22-Jan	-	28-Jan	Last week Interim	
5	29-Jan	-	4-Feb	Spring semester begins	
6	5-Feb	-	11-Feb		
7	12-Feb	-	18-Feb		
8	19-Feb	-	25-Feb		Prototype of steering and braking system
9	26-Feb	-	3-Mar		Prototype testing
10	4-Mar	-	10-Mar		
11	11-Mar	-	17-Mar		
12	18-Mar	-	24-Mar	Spring break	
13	25-Mar	-	31-Mar		Steering + Breaking System completed
14	1-Apr	-	7-Apr		Documentation
15	8-Apr	-	14-Apr	Easter weekend	Documentation
16	15-Apr	-	21-Apr		Documentation
17	22-Apr	-	28-Apr		
18	29-Apr	-	5-May		Final Report completed and edited
19	6-May	-	12-May	Last week of classes	Final Report turned in
20	13-May	-	19-May	Final Exams	

Appendix D - Estimate of Variable Costs

Table 9.2 – 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 9.2 - Thickness measurement of rotor with a Vernier Calipers

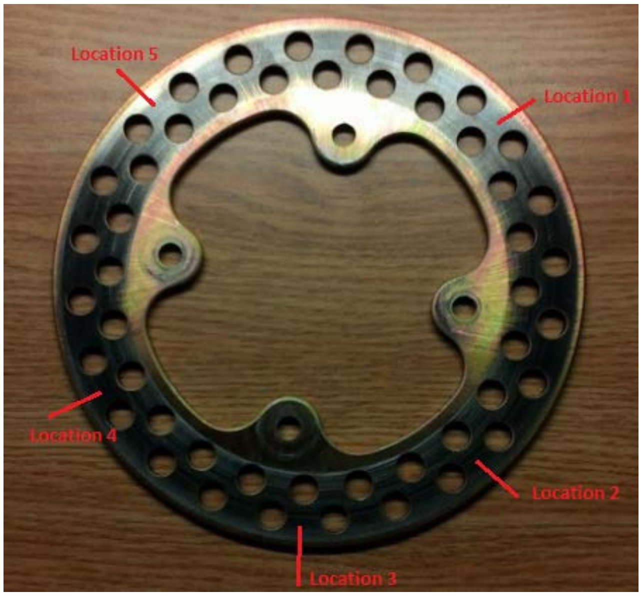

Figure 9.3 - Measure of Thickness Variation at Multiple Locations

Table 9.2 - 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.

Appendix F - Braking Calculations

The equation for stopping distance and values for the coefficient of friction is referred from *The Isaac Newton school of driving: Physics and your car* by B. R. Parker

Breaking Force on a Car

$W_{car} = 1409$ [lbm]

$W_{max,car} = W_{car} + 300$ [lbm] total mass applied; 300 pounds for two passengers. 150 for each.

$V_{max} = 25$ [mph] maximum velocity applied

Varables

$m_{car} = W_{max,car}$

$$v_{car} = V_{max} \cdot \left| 1.467 \cdot \frac{ft/s}{mph} \right|$$

$g = 32.17$ [ft/s^2] gravitational acceleration

$x = 32.17$ [lbm*ft/lbf-s^2] pound force conversion factor

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.

Stopping Distance

$$d_{stop} = \frac{{v_{car}}^2}{2 \cdot mhu \cdot g}$$ where mhu is the friction coefficient between tires and the road

$mhu = frict_{coef,bet,tires,\&,road}$

$frict_{coef,bet,tires,\&,road} = 0.6$

Friction for tires & roads is between 0.4 & 0.7; 0.7 for dry

Break Force

(1) Kinetic Energy of the Car

$$K = 0.5 \cdot m_{car} \cdot \frac{{v_{car}}^2}{x}$$

(2) Force required to stop

$$F = \frac{K}{d_{stop}}$$

Hydraulic Force Estimation

(1) Measured values

$P_1 = 40$ [lbf] Force applied to the brake pedal

$t = 0.1$ [in] master cylinder thickness

$d_1 = 0.875$ [in] master cylinder piston diameter

$d_2 = 1.0875$ [in] caliper piston diameter

(2) Estimation

$$A_1 = \pi \cdot \left[\frac{d_1 - t}{2}\right]^2$$ cross sectional area of the master cylinder

$$A_2 = \pi \cdot \left[\frac{d_2 - t}{2}\right]^2$$ cross sectional area of the piston cylinder

$$\frac{P_2}{A_2} = \frac{P_1}{A_1}$$ Force applied by the caliper; Pascal's law

$A_1 = 0.4717$ [in^2]

$d_1 = 0.875$ [in]

$\boxed{d_{stop} = 34.83 \text{ [ft]}}$

$frict_{coef,bet,tires,\&,road} = 0.6$

$K = 35711$ [ft-lbf]

$m_{car} = 1709$ [lbm]

$\boxed{P_2 = 64.94 \text{ [lbf]}}$

$v_{car} = 36.67$ [ft/s]

$\boxed{W_{car} = 1409 \text{ [lbm]}}$

$x = 32.17$ [lbm*ft/lbf-s^2]

$A_2 = 0.7659$ [in^2]

$d_2 = 1.088$ [in]

$\boxed{F = 1025 \text{ [lbf]}}$

$g = 32.17$ [ft/s^2]

$mhu = 0.6$

$P_1 = 40$ [lbf]

$t = 0.1$ [in]

$\boxed{V_{max} = 25 \text{ [mph]}}$

$\boxed{W_{max,car} = 1709 \text{ [lbm]}}$

Appendix G - Physical and Mechanical Properties of Materials

Table 9.3 – 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	-	-

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 below.

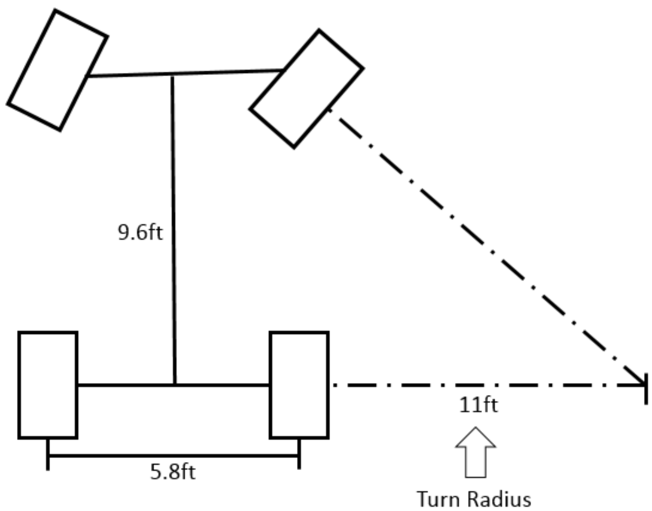

Figure 9.4 – Diagram of the turn radius.

Table 9.4 – 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 9.5 – 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 9.6 – 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.

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

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.

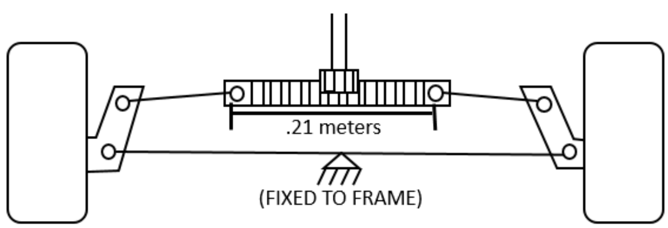

Figure 9.5 – Diagram of rack and pinion system

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 (Frank, 2006). This means the power output of the motor needs to be around 2000 kW.