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Next Generation Longboard Trucks NG-Trucks

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NG-Trucks

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Senior Project T489

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Table of Contents

Abstract

A device is needed that will provide longboard riders with a truck that is specifically designed for the sharp turns and high speeds they experience throughout their ride. This longboard truck must have a design that is engineered for these purposes and avoids the standard pin and bushing design that is commonly copied from the closely related skateboard truck. This standardized design is outdated, and more importantly, was made to adhere to the skateboard style of riding, consisting primarily of performing tricks with less turning. The longboard truck provides a secure connection point upon the two wheels and the board itself. Additionally, the truck provides a controlled ride by adding additional assistance with turns from leaning the wheels upon the y-axis, unlike the standard skateboard truck design that turns due to motions strictly upon the x-axis. The design enables a larger wheel diameter without sacrificing a low center of gravity compared to a normal truck by relocating the turning pins to the front of the truck instead of directly below it. The truck's functionality was first evaluated on Solidworks and then 3-D printed to ensure that the motion did not interfere with the structure of the board or the ride. This design offers improved maneuverability while providing a stable ride and a turning radius of just 6 feet.

Introduction

Description

This project reimagines the design of typical longboard trucks. This will address the high center of gravity disadvantage when using large wheels on a longboard due to the position of the trucks directly beneath the board. This will be addressed through relocation of the truck pin and improvement of the overall design in order to allow a larger diameter wheel without sacrificing the instability that comes with a high center of gravity. A larger wheel diameter gives the rider a smooth ride by dampening the impacts felt from rocks and cracks. Additionally, this design will allow the wheels to pivot about the y-axis, allowing tighter and more controlled turns. This pivoting motion also adjusts the wheel for the turn, decreasing the surface contact with the ground, and in return improving speeds and traveling distance by decreasing the friction resistance.

Motivation

The skateboard truck has not had a major redesign since the 1980s. Skateboarding and longboarding have progressed significantly as a sport in the last several decades and the design of the board should progress along with it. Because skateboarding does not have much in common with longboarding, it was interesting to consider the physical changes a rider may feel with a longboard with a truck designed for it. Research on the differences in riding style and purpose of these two boards indicates that longboards are designed for cruising and speed while a skateboard is better designed to perform tricks at low speeds. The difference in speed alone calls for a truck that is designed solely for a longboard, one that will lower the center of gravity and enable the rider to make smoother and more controlled turns. Additionally, lowering the center of gravity allows a lager wheel diameter, further enhancing the ride by dampening surface distortions.

Function Statement

The function of this longboard truck is to create a secure connection point between the wheels while allowing for larger wheels that do not raise the center of gravity.

Requirements

1) Must weigh less than 5 lbs. each
2) Fit a wheel with a 100mm diameter
3) Center of gravity no higher than 4 inches off the ground when unloaded
4) A maximum turning radius of 6 feet
5) Product must be weather resistant
6) Able to withstand a 300 lb. load directly above truck
7) Allow sharp and controlled turns

Success Criteria

1) The center of gravity is lowered in comparison with a typical truck when equipped with 100mm wheels
2) Weight requirement is met while the board remains strong enough to endure harsh impacts, bumps, stresses, etc.
3) Wheels will not contact the board at maximum turn
4) Corrosive resistant to endure normal wear due to weather and time

Scope of this effort

The complete product includes two trucks. One section will be secured to the board with an attached pin, which will also secure the second section while allowing pivoting/turning movements.

Benchmark

This design will be compared to a dual-pinned truck that has been purchased for a personal board. This truck is made with two pinpoints that greatly increase the turning radius. However, this design only raises the center of gravity compared to a normal truck. This is considered a top of the line truck regarding turning capabilities. The design will also be compared to a regular single pin skateboard truck.

Success of the project

The success of this project depends mostly on the tight turning radius of the board and height of the board with larger wheels wheel equipped. This truck design should also have a unique look and high durability to catch attention of potential buyers.

Design & Analysis

Approach

The goal of this project is to re-design a skateboard truck that is specifically engineered to allow large wheels while not sacrificing ride height. The truck that is commonly used today originates from the skateboard, which was designed for tricks traveling at low speeds on a smooth surface free of any cracks or imperfections. This project will create an appealing new truck design that eliminates road vibrations and enhances the speed and carving styles of longboarding.

A design was sought that will move away from the skateboard's pin-and-bushing method of turning and create a new method that relocates the pins to allow a larger wheel diameter. Ideally, this design will increase the turning capabilities of a board while increasing overall stability by lowering the ride height.

This inspiration for this model came from a previously designed truck that was modeled and 3-D printed during a Solidworks class. After inspecting the functionality of this design, it was determined that lack of stability and control was due to loose connection points and a range of motion that was too large for the model (see Appendix B-2). Modifications to this truck provided more secure connection points between the board and wheels while allowing for a leaning motion when going into turn (see Appendix B-1).

Design Description

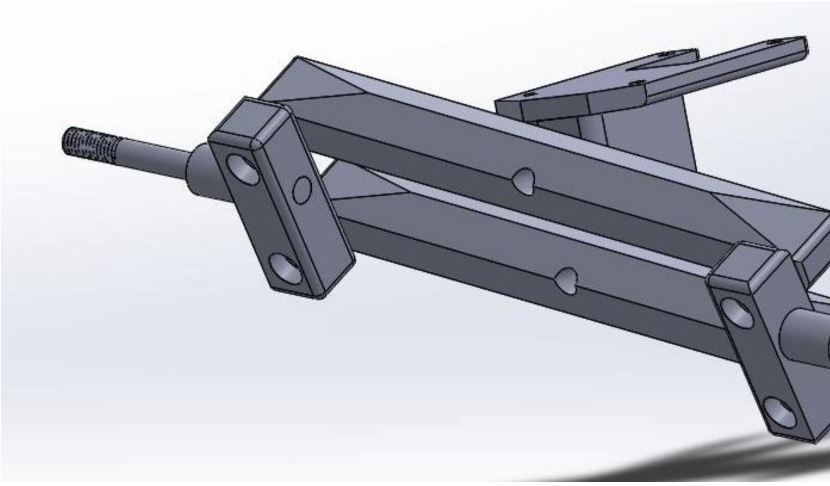


Figure 1: Concept Assembly - NG-Truck

Pictured above is an assembly screenshot of the NG-Truck before pins were inserted. Each hole represents a connection pin that will allow a swivel movement. The truck base will be mounted to the bottom of a longboard, allowing it to take advantage of the angle created when a turning motion is applied to the board. This angle will cause the bottom pin of the truck base to rotate outwards towards a wheel, implementing a movement on the main axles that will cause the outer wheel axles to break the usual perpendicularity the wheels have against the ground. This motion will be limited upon the truck base to ensure the turn does not become excessive, resulting in an ejected rider at increased speeds.

Benchmark

The benchmark of this design will be assessed against two other common truck types obtained from boards that are readily available. Performance will be assessed and recorded on these trucks using the same testing procedure used for the NG-Truck to create a comparison between the designs. This new truck design should meet the requirements to function successfully and ultimately perform at a higher level than its competitors.

Performance Predictions

The NG-Truck should weigh less than three pounds but will easily being able to withstand a 300-pound load placed directly above the truck. The leaning motion of the wheel will be able to increase the response of the truck when a rider begins shifting weight.

Description of Analysis

A-1: Outer Pin Sizing Diameter
A-2: Main Pin Sizing Diameter
A-3: Material of Connection Plates
A-4: Length Allowed of Connection Axle
A-5: Deflection of Connection Axle
A-6: Deflection at Wheels
A-7: Geometry of the Main Axles
A-8: Main Axle Geometry Comparison
A-9: Allowable Diameter of Main Axles
A-10: Material of Main Axle with Pin Hole Stress Check
A-11: Deflection of Main Axle

Further description of these analyses can be seen in the calculated parameters section below.

Scope of Testing and Evaluation

Most of the testing and evaluation of the NG-Truck took place fully assembled on a longboard alongside a second NG-Truck. Prior to testing, a truck was weighed to show a comparison when evaluating the different truck styles. After this was recorded, the longboard was assembled for testing.

The first evaluation took place on a consistent grid with a camera placed directly above the center to produce quantitative data related the turning capabilities of this design. Following this initial phase of testing, several different riders tested the models in a closed course. The riders used a ranking system to judge each truck design based on aspects outlined in the testing methods section. The subsequent rankings aid in overall design and success of the model.

Analysis

Design Issues

Many obstacles were encountered during the initial development of the NG-Truck. As previously mentioned in the design description, the design outlined in Appendix B-2 had to be reexamined due to a lack of stability and control. In order to move forward with this project, the first model had to be almost entirely redesigned. However, the original shape of the main frame was used in the new design, complete with a hexagonal section connecting the truck base to the wheel axles horizontally. These sections were relocated to the bottom of the board with both hexagon bars attached to the truck base, connected to one another at the wheel plates in a way that creates a swivel point across the wheelbase.

An additional issue arose when selecting the material for each section of the model. At first, aluminum was chosen as the material for all sections due to its lightweight properties. However, analysis indicated that a stronger material was necessary for this design and steel was chosen for the connection plates.

The level of clearance necessary for proper range of motion of the axles also presents difficulties. The sharp 90-degree angle of the base plate and the hexagonal shape of the main axles created a limitation in the leaning abilities due to a low clearance. This was be addressed by eliminating the sharp angle of the base plate to flow with the shape of the axles with much more ease.

Another design flaw was indicated with a weak point among the connection plates that go alongside the issues outlined above. This was be addressed by implementing the same angles as the base plate along with a change in material to steel.

Overall, the largest design issue encountered was the limited turning capabilities once mounted onto the longboard. This was caused by the leaning motion of the wheels alone not being enough to provide a movement necessary for a successful longboard truck. This was fixed by creating an additional range of motion at the point of connection between the truck base plate and the main axles, a concept that is outlined further in the discussion section of this proposal.

Calculated Parameters

The parameters outlined previously in the description of analysis section were calculated in order to inform dimensioning and material choices for the project.

A-3: The most important design parameters for a successful project are the material choices of each section. It was originally assumed that an aluminum of 5052 class or better would be suitable for each section, but additional analysis proved otherwise as in the instance of the connection plates (see Appendix A-3). This section was the most complex and handles much more stress in comparison to other sections due to the blunt force each wheel creates at a variety of angles. The analysis showed that aluminum is over three times too weak for the given maximum force and calls for use of steel with a strength exceeding 123psi. Material for the main axles is outlined below in A-10.

A-1 and A-2: Further analysis was carried out on two pin sizes for the connection plate point and the truck base plate points. These analyses indicated the minimum size allowed at each of these pinpoints with a safety factor of four included due to the uncertainty of blunt forces during sharp cornering with abrupt bumps. Although a size of just 1/8” is allowed for the connection plate pins, ¼” was used since it is easier to acquire and provides more stability. Similarly, the use of ¼” pins at the truck base would meet the design requirements but 5/16” was chosen instead as there is more stress concentration at these points.

The remaining analysis used the data gathered above to place design parameters on each section including the main axles, truck base, and connection plates. These design parameters keep weight requirements in consideration while providing dimensions that meet a maximum load requirement. These calculations implement a design factor ranging from 2.5 to 3.0, a range recommended in the Mott text when machine elements are under dynamic loading with uncertainty of loading in different scenarios.

A-4: A maximum dimension was given for the wheel axle extrusion to indicate how far away the wheel could safely sit from the connection plate. Although this is a maximum dimension, this value used was much lower than what was calculated to ensure that the bottom of the connection plate does not interfere with the ground at a maximum turn or leaning of the wheel.

A-5 and A-6: These analyses give a quantitative value for the amount wheel deflection that will result from application of a maximum force. This ensures that this connection will not deflect to a point that will allow for dragging of the connection plate and aids in construction of a stable design.

A-7 and A-8: The geometry of the main axles was finalized at this step. Taken from the original design shown in Appendix B-2, it was decided that inclusion of some sort of unusual geometry would increase visual appeal to the NG-Truck. However, the impact this would have on the structural integrity of the main axles had to be considered first. A hexagonal or octagonal axle was sought to provide a unique attachment angle at the pinpoints of each section. Although an octagon was initially desired for the angle present between its vertical and horizontal plane, Appendix A-7 shows that this reduced the integrity significantly. Because of this, a hexagonal axle was chosen as it was calculated to result in a more manageable 28% decrease in strength (see Appendix A-8).

A-9: The minimum axle diameter was given a quantitative value determine the size needed on the main axles. However, the given diameter will not work for the design, as the design necessitates a hole to be drilled in the center of the axle. This will be addressed in analysis A-10 below.

A-10: As mentioned above, the minimum allowable diameter of the axle could not actually be used for the design. In this analysis, a base value of 0.87” was sought and tested for given that this diameter can be fabricated from a 1” square rod easily. This analysis also approved the material of 5052 aluminum works for the design while hovering above a safety factor of 2.5, showing that a 5052 H-38 aluminum or better must be used for this design.

A-11: In this analysis, the deflection of the main axles was calculated in order to ensure that no interference with the ground would be present at maximum loading.

Best Practices

To account for uncertainties due to the random loading experienced during standard use of the truck, the Mott text recommends a safety factor of 2.5-3.0, a value commonly used in the industry. When it came to rounding and basic sizing, a higher value was used to maintain strength in the design.

Device: Parts, Shapes, and Conformation

The leaning motion upon the wheelbase of this design was inspired by modifications seen on cars, with the goal to utilize the idea of camber. More specifically, the negative camber improves grip while cornering by placing the tire at a better angle with the road. This transmits the forces exerted during cornering through a vertical plane down the tire instead of a shear force through it, shown in Figure 2. In this figure, the vertical force upon the inner (left) wheel applies to both wheels of the NG-Truck's design due to the angle being applied at each wheel during cornering.

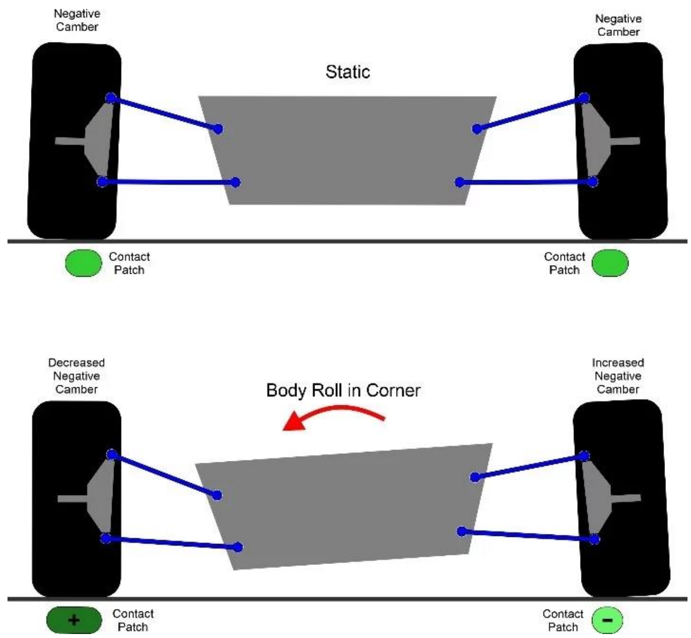


Figure 2: Contact when cambered

The geometry of the main axles provides a secure pivoting face between the pinpoints while shaving weight off the final project and increasing visual appeal.

Device Assembly, Attachments

Assembly of the NG-Truck consists of eight separate parts combined with four sub-assemblies. This begins with the welding of each wheel axle into the corresponding connection plates. The second sub-assembly consists of another weld mounting the base extrusion upon the base plate. The next step in the assembly involved securing the two main axles onto the truck base made in the previous step. The final assembly concludes with the attachment of the two connection plates on either side of the main axles (see Appendix B-3 to B-6). These connections will be made with six bolts and matching locknuts. This assembly process is repeated twice for a complete longboard set-up.

Tolerances, Kinematics and Ergonomics

Most of the dimensioning across the design does not require significant tolerances due to the amount of clearance throughout the sections. This allows for a higher general tolerance of +/- 0.1”, except in areas that carry additional purposes as outlined below. Providing this tolerance will reduce machining time and the possibility for failed parts as well as a reduction in cost.

B-3: Areas of importance in drawing 20-001 include the pinholes where the main axles attach and where the base plate mounts onto a longboard. These dimensions are a minimum to allow insertion of a purchased bolt. The other section requiring a smaller tolerance is the area connecting with the longboard. Because this section handles a lot of stress from riding, this dimension is a minimum so it cannot get thinner and weaker.

B-4 & B-5: For drawings 20-002 and 20-003, an additional tolerance is needed where the wheel bearings slide on, shown as a maximum. This section also shows a minimum to ensure there is enough space to fasten a locknut to secure the wheel onto the axle. The other special tolerance includes the pinholes on the connection plates, which is to allow adequate room to insert and secure the pins.

B-6: Drawing 20-004 only requires additional tolerance for the pinholes as mentioned above and the location of these pinholes to ensure a proper distance from the truck base to both wheels.

Methods & Construction

Description

Central Washington University provides a wide range of manufacturing methods, including CNC machines, mills, and lathes. This design was tested using 3-D printing to ensure working functionality of the moving parts and manufactured using a combination of a mill, lathe, drill press and sander. Before any cuts are made, the 3-D printing tests gave valuable insight on some possible changes that had to be made to increase the performance of the final design. One of these altercations included changing the connection angle between the connection plates and base extrusion by including another connection point at the center of the main axle, seen in Appendix B-6. This fixed the interference that was limiting the turning capacity of the design. This 3-D printing took place outside of the classroom with a personal-use printer to eliminate the possibility of restrictions on availability at the university.

The device consists of a total of eight working parts including the truck extrusion, base plate, two main axles, two wheel plates, and two wheel axles, as well as six pins and six nuts to hold the model together. The wheel axles were pressed fitted and welded onto the wheel plates. The wheel plates will be mirror replicas of each other to hold a wheel on either side of the truck. The pins give free range of motion to allow a leaning motion of the wheel and turning motion of the longboard (see Appendix B). Two complete devices are needed in order to build a complete longboard.

Once the design of the device was reviewed and improvements were made, the manufacturing process began with a raw hex bar of 2140 aluminum alloy and 4140 steel bars. These series of material were required due to the lower series falling below stress standards during analysis (see Appendix A).

Construction

The main sections of the truck were manufactured using Central Washington University's resources such as a mill and lathe machine to fabricate the design from the raw material stated previously. The bolts and nuts were purchased separately from a local Fastenal to ensure reasonable cost and time efficiency. The construction of these sections was completed in a specific sequence including the eight sections and three sub-assemblies, as outlined below in the drawing tree. The connection plates were manufactured following a series of two steps for the milling work, followed by the lathe (see Appendix B-5). The mill used to fabricate the basic outline of each of these parts to generate a product that was close to completion, after which a lathe was used to add the final cylindrical features of the design. As seen in the drawing tree below, there was three sub-assemblies before the final project was assembled. These assemblies were created in order to save time and money when it came to material waste along with cutting down on milling time.

The first sub-assembly consists of welding of the two sections that make up the truck base, seen in Appendix B-3 and B-4. Although a welding process was originally avoided due to availability, it was decided to add this process in since it would have costed roughly $100 more to buy a raw piece of steel large enough to mill this part as one. Along with this savings, milling time was also shorter due to the ability to buy the sections within 0.25" of what the final product needs to be. Although there would be an additional cost to weld these sections together, these savings made this decision well worth it in the end.

The second sub-assembly that must be completed prior to the final assembly consists of inserting a wheel axle into a press fitted hole drilled into the connection plates, seen in Appendix B-5 and B-7. Since this is a loose fitting, the wheel axle was welded to the wheel plates to provide a secure connection between the two parts. This wheel axle was purchased as a raw piece of strengthened steel to be inserted into the connection plates in order to form a section that a longboard wheel can fit on. At first, the length that this called for was too large to be ordered in one piece and would have accounted for a lot of unnecessary waste. By separating this into two different sections, money was saved by allowing the four connection plates to be milled using just three inches of steel bar compared to over 12 inches if manufactured together, thus allowing the purchase of a 1 foot bar compared to a 1.5 foot piece.

The main axles, seen in Appendix B-6, are manufactured using only a few steps. Since hexagon rods are available in a vast amount of material on McMaster-Carr, these were purchased to save hours of milling time. The 32 inches of 2024 aluminum alloy hex rods requested for this project were purchased for $45. Although it's cylindrical counterpart could have been purchased for only $32, the time buying the hex shape would save far surpasses the $13 difference. All that was left to be done for the manufacturing of these axles was to be cut to size, chamfered at each end, drilled, and milled for the final connection point at the truck base. This saved upwards of eight hours thought to be needed in order to mill the shape out of a cylindrical rod.

Six out of eight parts went through a milling process, with the only exception being the two wheel axles. For this, 50 thousandths of an inch was cut off at a time using a ½ inch, four flute milling bit. This manufacturing process was the most time consuming due to the vast amount of material that was needed to be cut off. In some instances, upwards of over 1 ½ inches needed to be cut, calling for a total of over 300 sweeps to get the final part. For this reason, the parts for both trucks were milled simultaneously in order to save time by manufacturing up to 4 parts at a time.

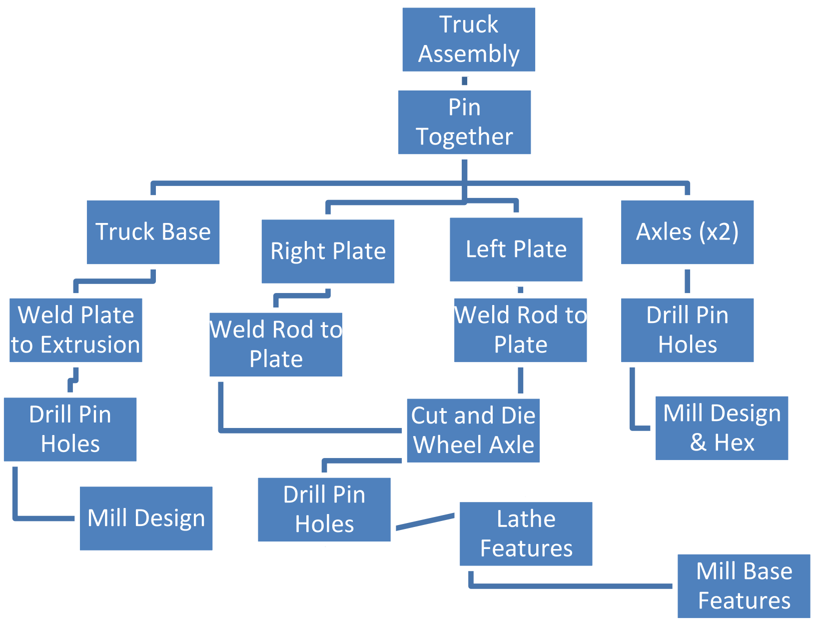
Two out of the eight parts required a lathe machine in order to provide clearance between the wheels and the connection plates, seen in Appendix B-5. For this process, both connection plates were milled to the base size leaving a 0.6 inch square sticking out of each plate to allow a cylinder to the be turned. Using a 4-jaw chuck, the parts were secured in the lathe and aligned with the center of the square. The part was then turned at 450 rpm and shaved down to the required diameter being fed slowly by hand to avoid contacting the plate. This process was much quicker, with the alignment being the most time consuming portion.

The two wheel axles only had to be cut down to size and threaded using a 5/16-18 die. Seen in Appendix B-7, each axle was threaded approximately ¾ inch down the rod. It was important to use plentiful die oil and make a reverse cut for thread quality along with prolonging the life of the die.

As stated previously, a welding process was added in order to save numerous hours of milling time. Although there was a $120 cost to purchase welding supplies the only alternative was to mill the shape from a large bar and McMaster Carr (along with other distributers) doesn't stock bars large enough to allow milling of a 3 ½ X 2 ¼ X 2 ¾ inch part. However even if a company did, the wasted material would be over 50%. This would not only take days of milling time making thousands of cuts but would also waste most of the budget just on mill shavings. The solution, separating the section into two parts. Seen in Appendix B-3 and B-4, these parts were purchased from bars of steel almost already cut to shape, only needing a slot cut into both. These two 4140 bars were only $51 compared to an amount over $150 for the large bar, saving a total of over 34%. By adding this process, welding the wheel axles into the connection plates instead of press fitting saved the hassle of purchasing the prefect size reamer to make this hole.

For the specialty bolts needed for the pin locations, a local Fastenal provided access to their inventory free of charge to assist CWU students with senior projects. This made the construction simple by being able to test different sizing and make changes throughout the quarter.

Drawing Tree



The axles are added to the truck base assembly first to give consistency throughout each test of the product. This will eliminate any stress concentrations caused by any misalignment of the wheel plates.

Parts List and Labels

The parts listed in the drawing tree above are referenced in Appendix C.

Testing Method

Introduction

The success of the device was gauged by comparing its performance to two other skateboard truck designs that were easily acquired for the project. Failure to meet the set requirements indicate the design does not outperform the trucks that are commonly used today and is likely a product that will not sell to distributors. This would necessitate a change be made to the design to correct performance issues.

A successful design was specifically engineered to account for the physical style differences between skateboarding and longboarding and does not sacrifice any weight while improving maneuverability and control of the board during cruising and speed riding styles.

Methods Approach

The requirements listed in the introduction of this proposal account for the weight, center of gravity, turning radius, loading, and overall control of the NG-Truck. Each design was graded by the following methods in order to assess the product's success. The tests were conducted in a controlled and repeatable environment to ensure collection of reliable data. The maneuverability of this design was tested on a grid outlined with tape with equidistance between each line. This grid was directly below a recording camera to give accurate measurements of the testing area. A series of volunteers have ranked the different truck designs on unique terrain areas. The following procedure was recorded inside and around Hogue Hall at Central Washington University.

Test Procedure

When testing this project, at least 6 hours should be available in order to allow time to set up the testing area, conduct each test for the 3 separate truck designs, and assembly/disassembly of the longboard multiple times. The data used for this project was gathered both in the open lobby of Hogue at Central Washington University along with the sidewalks surrounding this building. The lobby will be used to test weight, center of gravity, loading, and the turning radius of each setup along with all assemblies. The surrounding areas of the building will be used to put comparable numerical data on the maneuverability, stability, and ride comfort. These tests should be conducted on the same day to eliminate any weather variables.

In order to complete these tests, the needed resources include a tape measure, painters' tape, cones or similar object, scale capable of measuring to the 1/10th pound, tools for assembly, and a recording device that can be placed directly above the grid area. Additionally, the NG-Trucks are obviously needed with two different normal trucks, one standard longboard deck, and a set of oversized 100mm wheels.

Step1: Use tape measure and painters' tape to lay a 15 foot by 15 foot grid below a video camera outlined with 1 foot squares inside.

Step 2: Outline the outside course with cones or more tape. This must consist of a turn at a high speed (Course 1), cones placed 4 feet apart in a line on a downhill surface (Course 2), and a steep downhill surface with cones in a slalom style with 15 feet of lateral movement every 30 feet of forwards movement (Course 3).

Step 3: The weight of a single truck is taken before the longboard is assembled. This is tested on a scale to one tenth of a pound. Record value in table provided below.

<u>Step 4:</u> From this point on, a complete longboard setup with two trucks is tested. Assemble the two trucks upon the longboard. Attach the 100mm wheels.

<u>Step 5:</u> The center of gravity is measured with three distances. The first is the height of the bottom surface of the longboard, *Height*. The second is the distance between the center of the front wheels to the center of the rear wheels, *Distance 1*. The third is the distance between the center of the wheels on the same axle, *Distance 2*. Record these values in the table provided below.

<u>Step 6:</u> The turning radius is gathered upon the grid mentioned previously. Record a video of three 180º turns riding over the grid as tight at the trucks will turn. Reference back to the video and use the grid to fill in the table.

<u>Step 7:</u> A 300-pound load is tested by standing directly above the truck with additional weight. This is recorded as a test or fail in the table. Note any deflections or discrepancies upon the truck.

<u>Step 8:</u> To compare the maneuverability, rank the truck set on a scale from 1-5 (worst-best) on each of the three courses. Add any additional notes on ride quality in the table as well to compare results later. A guideline has also been provided in the appendix to help fathom the scale.

<u>Step 9:</u> Repeat steps 3-8 for the remaining two truck types.

Proposed Budget

Part Suppliers, Substantive Costs, Sequence and Buying Issues

The material for the main sections of the design including the axles, truck base, and connection plates were purchased from McMaster-Carr. Since buying mass quantities of nuts and bolts was not suited for constructing just a single pair of NG-Trucks, these items were purchased from a local Fastenal store. Before purchasing the raw material from McMaster-Carr, the inventory at Central Washington University was checked in attempt to save time and money. This inventory did not contain the correct metal or sizes needed for any of the sections.

Determine Labor & Estimate Costs

Central Washington University personnel assisted with the fabrication and manufacturing of the sections, eliminating labor costs. However, there are outstanding rates as the budget items will be reimbursed. A breakdown of the budget is referenced in Appendix D, where labor and material estimates are included if the services were not provided by the University. This includes the total cost to complete two NG-Trucks as needed for one longboard.

Labor

As mentioned above, there were no foreseen labor costs. The total amount of fabrication and assembly hours for this project was 46.3 hours, or $544 out of the $750 it costs to complete the entire project. This includes welding time but not assembly of each section.

Estimate Total Project Costs

A breakdown of the total costs for this project can be referenced in Appendix D. Here, the base pay of $15 per hour for labor was included in the estimated total to give an idea of the cost of this project if this work was performed on company time. The total estimated cost of this project, including labor and part materials, came out to be $750. When it came time to purchasing the parts, the actual cost was almost spot on the estimate, only differing by a $50 shipping cost that was not taken into account previously. This represents the cost of all metal being $207 and does not consider the labor costs since the project was constructed on personal time. This sum includes purchasing of the following items; 3 feet of 2024 aluminum hex bar, 3 feet of 1144 high strength carbon steel 8mm rod, and three different sized 4140 multipurpose steel including ¼" X 2 ½", ½ foot of 1" X 2 ½", and a foot of 1 ½" X 2 ½". This includes everything needed for two longboard trucks excluding the pins.

When it came time to testing of this project, it was also realized additional materials would need to be purchased including a set of oversized wheels and grid tape. The wheels were needed to show how the trucks work when equipped with over-sized wheels, which is a requirement of the project. The largest commercially available size was 100mm, so this is what was used on each of the three truck types for testing. The tape was needed to lay out the grid to measure the turning radius. These purchases added an additional $48 to the budget, bringing the total project cost to be $305. This put the project over budget by 35%.

Funding Sources

It is expected that a portion of material and personnel labor will be donated by Central Washington University. Upon visiting a local Fastenal, the employees offered access to their inventory for this senior project which covered all specialty bolts, nuts, and washers. Fastenal also supplied some nuts through their donation to Central Washington Universities machining lab. The rest of the costs were covered by the designer.

Proposed Schedule

High Level Gantt Chart

The scheduling chart can be seen in Appendix E. Here, prospective dates for completion of different tasks can be seen alongside an estimation of time needed to complete them. The zones highlighted in green refer to the estimated duration to complete the task while the 'X' defines when that task was delivered. As shown in the Gantt Chart, fall quarter was reserved almost entirely for design and analysis of this project. Winter quarter is reserved for the manufacturing, fabrication, and assembly of the project along with updating the proposal and website. The last quarter consists of the testing and improvements. This schedule assisted with time management and efficiency as the project moved forward.

Specify Deliverables

Specific tasks have been assigned to ensure that the fabrication of this project can be completed well within the time requirement of 10 weeks. Since two devices are needed to complete a longboard, this project manufacturing began by cutting parts for each truck sub-assembly simultaneously so the overall construction would be reduced in the long run. This allowed the sections of the part to be completed much sooner than previously estimated. As you can see under the green sections in the Gantt chart, the two trucks were originally planned to be completed at separate times. However, once the manufacturing processed began, the time saved by not having to reposition each part twice for each truck made it obvious to do so. Therefore, X's can be seen before the scheduled time in the Gantt chart. As shown in Appendix E, the NG-Trucks were constructed during the first four weeks of winter quarter. Following manufacturing, these parts were assembled towards the end of the quarter with the welding and pinning methods.

Estimate Total Project Time

Outlined in Appendix E, the total time to create this project was estimated to be 103 hours, accounting for the analysis, proposal, manufacturing, and assembly of two NG-Trucks. This time also includes the time spent on the proposal, analysis, and drawings included in project. The actual time this process took to complete ended up being 150.8 hours, 67% over estimation. This was due to the extensive analysis and project design changes throughout the two quarters. The testing section of this project was estimated to take a total of 60 hours, and took 64.4 hours. This testing time was much easier to predict since there were no major surprises unlike the first two quarters of the project.

Project Management

Human Resources

Given that this is an independent project, it was much easier to set work times without having to manage the typical scheduling issues associated with group projects. Class time and office hours were used to receive guidance and support from advisors and mentors.

Physical & Soft Resources

Central Washington University offers a wide range of resources to students, including machinery, materials and assistance with outside funding. This project utilizes the availability of the vertical drill press, milling machine, and lathe to eliminate any need for casting materials. Although there was no matching stock to use for this project, Central Washington University has an inventory of scrap pieces that could have been utilized if this project had more flexibility regarding material or sizing. Instead, the raw materials were purchased from McMaster-Carr. The hardware was purchased from a local Fastenal. Before any fabrication took place, the design was tested using a 3-D printer outside the classroom. In addition to these physical resources, the CAD labs on campus were utilized for work on the Solidworks designing of the project.

Financial Resources

The materials needed to complete this project are of low quantity and small size. This will eliminate the need of pursuing any sponsorships outside of what is already available for use. Central Washington University provided the machinery and labor while a local Fastenal provided the pins, bolts, and nuts.

Discussion

Design Evolution

The basic design of the NG-Truck changed significantly over the first few months. The original design, seen in Appendix B-2, was a rough idea thrown together during a previous student's Solidworks project. However, a variety of changes were made to this original design. Several problems were seen in the first design including a stress concentration at the pinpoint, and many issues regarding stability would have arisen during testing the range of motion due to the simplicity of the connection between the truck base and the main section of the design. Almost all this design was scrapped and re-thought to allow more control and reduce any stress concentration. Only the original hexagonal shape of the axles was left unchanged.

Once the new design was sketched, there were a few more changes that were necessary to create a specially engineered longboard truck. An idea of these design flaws was anticipated throughout the design process, but an optimal solution was not available until there could be proper testing. Two major flaws were discovered that needed to be addressed after testing a 3-D printed assembly of this design, the clearance between the main axles and the truck base while a leaning motion was applied and a lack of mobility of the truck to allow sharp cornering.

The first flaw to be fixed came about clearances between the tip of the hexagonal shape of the axles and the flat surfaces where pinned to another section, such as the main axles to the truck base, and the main axles onto the connection plates. This problem was caused mostly from the blunt 90-degree sectioning where a pin would be attached. This was relatively simple to fix, with chamfers applied at the center of the base extrusion that were more consistent with the hexagonal shape. This cut allows for much more motion about the main axles.

The second design flaw was not as easily addressed as the first, as this required additional range of motion in the design. This was necessary because the leaning motion of the design did not produce an adequate amount of turning of the longboard assembly. There were a few solutions to this issue to consider. The first idea, sketched in Appendix B-8, was to insert an extra pivoting area on each of the connection plates in order to allow a forward/backwards motion at the wheels. This would allow the wheel to pivot back or forth with cornering, but there was not much confidence in a controlled motion since the wheels wouldn't be mimicking each other's movements. The second idea, sketched in Appendix B-9, was to insert a vertical pivot upon the main axles on either side of the truck base before reaching the connection plates. This design allows more movement of the wheel in comparison to the previous solution, along with more control due centering of the pivot. Appendix B-10 shows a sketch of the design solution that was thought to be most successful. The goal was to change the connection between the main axles and truck base in order to add movement of the wheels forward and backwards in addition to the leaning motion.

Figuring out where to add this additional range of motion was only the first step when it came to implementing this range of motion. The next step was deciding how to implement this pivot point upon the design while not interfering with the swivel motion that allows the wheels to lean. To address both obstacles, a few solutions were brainstormed. One being to add ball joints upon each connection point of the main axles. However, this would cause the axles to rotate upwards towards the longboard deck and possibly cause interference while in use. Another solution was to add a clevis upon these same pivot points. This method would eliminate any possibility of pivoting in a way that would cause interference but in return might allow there to be an uncontrolled pivot in the direction that is needed. By combining these two ideas and using a clevis on the top pin and a ball joint on the bottom pin, the additional range of motion could be implemented without sacrificing stability.

Although the solutions outlined above were all considered before manufacturing the project, it was believed that these connections would have caused the trucks to become too loose due to the additional pivot point. Even if this was a minor flaw, it was decided that any additional pivot point upon the system would be avoided. In order to implement a design change that improves maneuverability without adding any additional pivot it was decided to change the connection between the main axles and the base extrusion. Seen in Appendix B-6, the middle of the axle had an edge that was milled down by 0.2 inch so the connection plates would not attach to the main axles on the same plane that the base extrusion does. Reference the original drawing of the main axles at Appendix B-12 to further visualize this change. By providing this connection point on a different plane than the connection axles, a slight wheel movement forward or backwards occurs with the turning motion of the longboard. Additionally, the connection plates, seen in Appendix B-5, were then able to be simplified substantially down to a bar with a single extrusion coming out. If this change would have been applied before the purchasing of materials, additional money would have been saved by cutting the amount of material needed for the connection plates in half, as well as a reduction in the manufacturing time. A visualization of the design before the connection plates were made can be seen in Appendix B-13.

The initial design was altered even before the significant changes discussed above were made (shown in Appendix B-1). Originally, an attempt was made to avoid drilling a hole through the center of the axles by instead securing a pin onto each axle, but this design was deemed unnecessary as long as the axles were enlarged slightly to account for stresses created by drilling a hole in the middle of each axle. This cut down on fabrication time and made the design simpler overall by allowing a standard pin in this section instead of special fabrication.

During the manufacturing of this project, a few issues had to be dealt with while milling the raw steel. The first came from the ½-inch mill bit not having enough cutting area in order to cut the 2-inch depth of the connection plates. By rotating the bar 90 degrees, this depth was easily milled for the slot upon each section. Although this eliminated the fillet on the inside of this section, this was not a problem as most of the load would be implemented upon this same cut on the truck extrusion section. With this truck extrusion cut only being out of a 1-inch bar, this fillet was still able to be milled as planned.

In regard to the testing process of this project, the design ended up performing surprisingly well when compared to two regular skateboard trucks. The testing procedure overall went pretty smooth, only running into a couple issues regarding where to place the grid to measure turning radius. Since Hogue was not unlocked during testing time due to the coronavirus lockdown, the grid was setup outside the building. The filming of this process proved challenging because the team was not able to get the camera directly above the testing area. This caused the video to be slightly off to the side, but this is an adequate amount to see the turning radius measurements of each set of trucks. Once compared, the NG-Trucks were able to show a 15% smaller turning radius than its competitors.

Future Improvements

Although the NG-Trucks are functional and seem to outperform their competitors, they are still the first prototype and can be improved in a few ways. The implementations outlined below would improve the quality of the ride and enable the trucks further outperform competitors.

Insertion of a spring in the truck that would allow the truck to come back to the neutral position would be the most important improvement to the ride. Without this feature there is increased strain on the rider's ankles caused from keeping the board in the correct position.

Another modification that should be made is the addition of bearings at the six pinpoints. Not only would this eliminate noise caused from the friction, it would also make transitioning into turns feel much smoother.

The NG-Trucks are designed to be used with large, spherical shaped wheels to utilize the leaning feature of the truck that is visualized during turns. This would provide a constant amount of contact with the ground and more evenly distribute the forces seen upon each wheel. This large wheelbase allows for wheel up to 10 times the normal size, improving the ride quality by absorbing more vibrations caused by bumps and cracks in the riding surface.

Project Risk Analysis

There are always certain risks involved when dealing with moving parts and fabrication and the use of personal protection equipment (PPE) during the manufacturing of the NG-Trucks was important. The Job Hazard Analysis form can be seen in Appendix J, where proper PPE is outlined for each job type seen while creating this project.

Success

Given the complexity of this project, it was to be deemed successful if it could be used as a typical longboard truck. With that being said, additional tests and comparisons were taken in order to gauge the actual purpose of this project, creating a truck that is specifically engineered for longboard style riding.

Project Documentation

This project has been documented throughout this report with the analysis referenced in Appendix A, the drawings for each section in Appendix B, and the completion schedule being outlined in Appendix E.

Results

After gathering and comparing the results, the trucks performed surprisingly well compared to both the Reverse and Traditional Kingpin Trucks. On average, the NG-Trucks performed 32% better compared to the RKP and TKP Truck types overall. Showed in the graph in Testing Appendix, this project was able to lower the ride height by 0.8” equipped with 100mm wheels, decrease the turning radius by over 3.5 feet, and spread the weight area by 36%! This spread area is a good way to visualize the ride stability and refers to the area between all four wheels, where the riders' weight is dispersed. Although the NG-Trucks do weight about 2.5 pounds more than the competitors, some parts were made from steel since they could not be casted in the available foundry as an aluminum alloy. Making the switch to steel eased the manufacturing process since these parts were then welded together. Therefore, this weight can be reduced substantially by a slight change to the manufacturing process!

Conclusion

A model has been created that should meet the function requirements presented in this report. A remodel was printed and tested before the device was ready to be created. The parts list and budget for the complete project can be referenced in Appendix C and D. The analysis in Appendix A show that these parts and dimensioning will be successful.

Acknowledgements

This project could not have been completed without the resources provided by Central Washington University. A special thanks goes out to the mentorship of the CWU MET faculty including Dr. Johnson, Professor Pringle, and Dr. Choi, who gave valuable insight and guidance when it was needed most.

References

"Machine Elements in Mechanical Design" Sixth Edition, Robert L. Mott

www.McMaster.com

https://www.tevo.cn/products/3d-printers/tevo-nereus/

Appendix A – Analysis

A-1 – Outer Pin Diameters

Outer Pin Diameters | MET 489 | Analysis #1

Given

Max 300# load evenly distributed on board (above truck)

Pins in single shear

Grade 2 bolt

Safety factor 4

Find

Shear stress on pins

min pin diameter

Assume

Rigid material

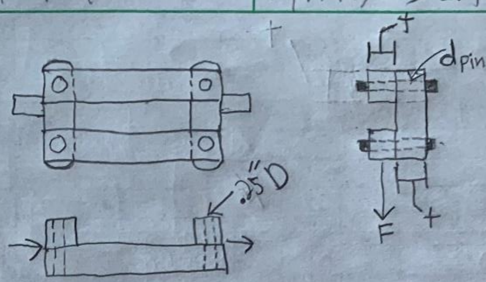
Homogenous

Method

Equilibrium

Area

Shear



Solution

$\tau_{ave} = \frac{F}{A}$

$F_{max} = 150\#$

$A = \frac{\pi (0.25)^2}{4}$

$A = \frac{\pi (.125)^2}{4} = 0.01227 in^2$

$A = \frac{\pi (.0625)^2}{4} = 3.07 \times 10^{-3}$

$\tau = \frac{150\#}{\frac{\pi (.25)^2}{4}} = 3056 psi$ for $\frac{1}{4}$" pins

$\tau = \frac{150\#}{.01227 in^2} = 12223 psi$ for $\frac{1}{8}$" pins

$\tau = \frac{150\#}{3.07 \times 10^{-3}} = 48892 psi$ for $\frac{1}{16}$" pins

Grade 2 bolt

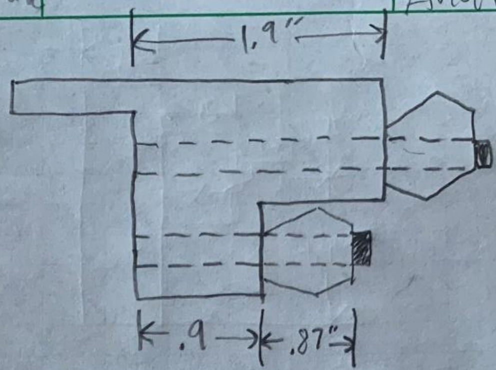
$S_y = 60 ksi$

Design allows for $\frac{1}{8}$" pins with an added safety factor of 4

$12223 psi (4) = 49 ksi < 60 ksi$

A-2 – Axle Pin Diameter

Base | Axle Pin Diameter | Analysis #2



Given

Pins in single shear

L=300#

Picture shown

Grade 2 → S_y=60ksi

Find

Shear stress & pin diameter for N>3

Assume

5/16" D or

1/4" D or

3/8" D

Homogeneous

Method

$\tau = \frac{F}{A}$

Solution

$\tau = \frac{NF}{A}$

For 1/4" Pins

$$A = \frac{\pi(.25)^2}{4} = .0491 in^2$$

$$\tau = \frac{150\#}{.0491 in^2} = 3056 psi$$

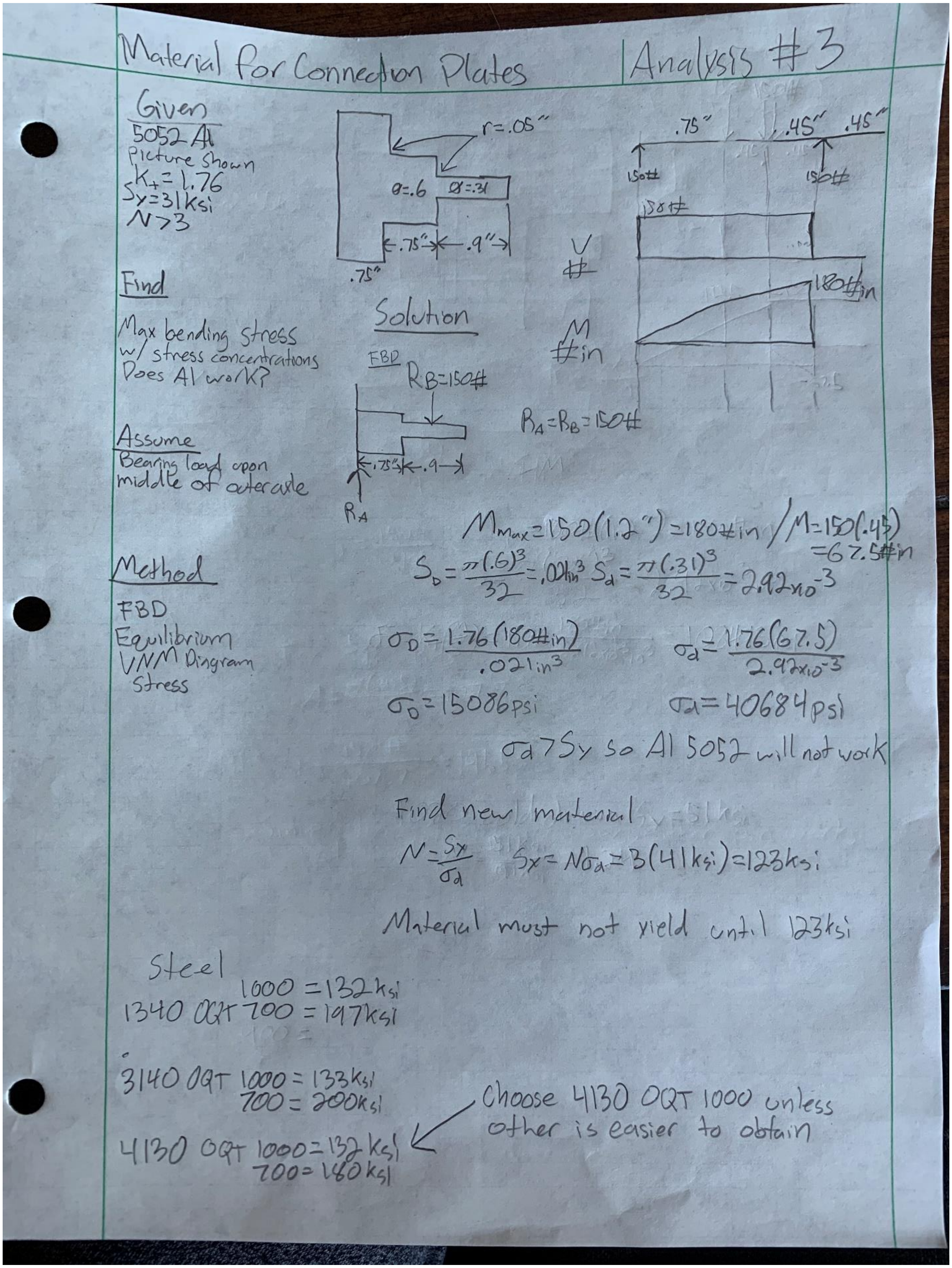
For 5/16" Pins

$$A = \frac{\pi(.3125)^2}{4} = .0767 in^2$$

$$\tau = \frac{150\#}{.0767 in^2} = 1955 psi$$

Since shear stresses are low, either pin works and grade 2 steel is more than enough

A-3 – Material of Connection Plates



Material for Connection Plates | Analysis #3

Given
5052 Al
Picture Shown
$K_t = 1.76$
$S_y = 31\,ksi$
$N > 3$

Find
Max bending stress w/ stress concentrations
Does Al work?

Assume
Bearing load upon middle of outer axle

Method
FBD
Equilibrium
VNM Diagram
Stress

Solution

$R_A = R_B = 150\#$

$M_{max} = 150(1.2") = 180\#in$ / $M = 150(.45) = 67.5\#in$

$S_D = \frac{\pi(.6)^3}{32} = .021in^3$ $S_d = \frac{\pi(.31)^3}{32} = 2.92x10^{-3}$

$\sigma_D = \frac{1.76(180\#in)}{.021in^3}$ $\sigma_d = \frac{1.76(67.5)}{2.92x10^{-3}}$

$\sigma_D = 15086psi$ $\sigma_d = 40684psi$

$\sigma_d > S_y$ so Al 5052 will not work

Find new material

$N = \frac{S_y}{\sigma_d}$ $S_y = N\sigma_d = 3(41ksi) = 123ksi$

Material must not yield until 123ksi

Steel
1340 OQT 1000 = 132ksi
700 = 197ksi

3140 OQT 1000 = 133ksi
700 = 200ksi

4130 OQT 1000 = 132 ksi
700 = 180ksi

Choose 4130 OQT 1000 unless other is easier to obtain

A-4 – Length of Connection Axle

Length Axle Extrusion | MET 489 | Analysis #4

Given

Design factor = 4

Dimensions shown in picture →

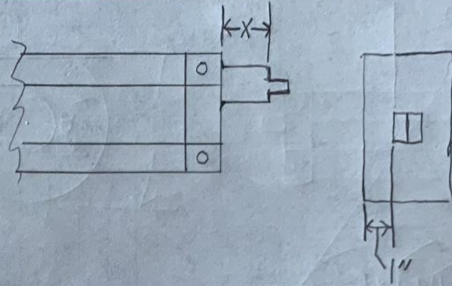
1015 Steel yield = 60ksi

5052 H34 yield = 31ksi

wheel overhang = 1"

Load Max = 300#

D = .625"



Find

Minimum value of X to allow free travel of wheel.

Max value of X before failure.

$X_{min} = 1.25"$ (measured)

X_{max} = Distance allowed without failure

Assume

Secure connection to body

Rigid body

Homogeneous

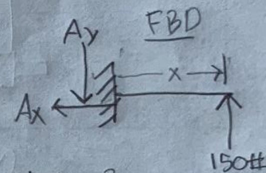
Constant, stationary load

Method

FBD

equilibrium

Solution



$$\sigma = \frac{Mc}{I}$$

$$I = \frac{\pi D^4}{64} = \frac{\pi(.625)^4}{64} = 7.49 \times 10^{-3}$$

For 1020 cold steel

$$\frac{60000\ psi}{4} = \frac{M(.3125")}{7.49 \times 10^{-3}}$$

$M_{max} = 359.5$ #in (with added design factor)

$$X = M/F = \frac{359.5\text{\#in}}{150\#} = 2.4\text{in}$$

For 5052 H34 Al

$$\frac{31000}{4} = \frac{M(.3125")}{7.49 \times 10^{-3}}$$

$M_{max} = 185.75$ #in

$$X = M/F = \frac{185.75}{150\#}$$

$$X = 1.24"$$

A-5 – Connection Axle Deflection

Given

1020 Steel cold drawn / 1060 Al

Max load = 300#

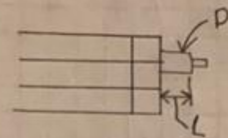
L = 1.25"

D.F. = N = 4

$S_y = 51$ ksi

$E_s = 207$ GPa $= 30\times10^6$ psi

$E_A = 10\times10^6$



Find

Deflection if axle D is 0.625" and 0.5" for steel & Al alloy

Assume

Rigid body

weight of axle neglected

Minimal Deflection

Method

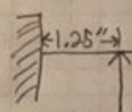
FBD

I

Deflection

Solution

FBD



$$y = \frac{-PL^3}{3EI} \rightarrow I = \frac{\pi D^4}{64}$$

For 1020 steel

$$I = \frac{\pi(.625)^4}{64}$$

$$I = 7.49\times10^{-3}$$

$$y = \frac{-PL^3}{3EI}$$

$$y = -\frac{(150\#)(1.25")^3}{3(30\times10^6)(7.49\times10^{-3})}$$

$$y = 0.00043"$$

$$I = \frac{\pi(.5)^4}{64} =$$

$$I = 3.07\times10^{-3}$$

$$y = -\frac{PL^3}{3EI}$$

$$y = -\frac{(150\#)(1.25")^3}{3(30\times10^6)(3.07\times10^{-3})}$$

$$y = 0.00106"$$

For 5052 H34 Al

$$y = -\frac{150\#(1.25")^3}{3(10\times10^6)(7.49\times10^{-3})}$$

$$y = 0.0013"$$

$$y = -\frac{150\#(1.25")^3}{3(10\times10^6)(3.07\times10^{-3})}$$

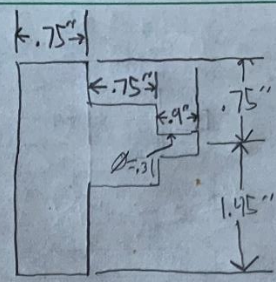
$$y = .0032"$$

A-6 – Deflection at Wheel

Wheel Deflection | | Analysis #6

Given

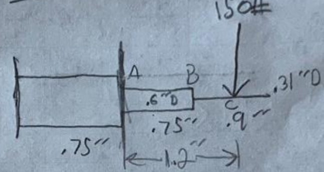
ID of bearing = .31″
5052 Al / 4130 steel
picture shown
$S_y = 31$ ksi (Al)
$E = 10\times10^6$ psi
Load = 300#



Find

Deflection at wheel
Can a typical bearing ID be used?

FBD



$A_{A\text{-}B} = \frac{\pi(.6)^2}{4} =$

$A_{B\text{-}C} = \frac{\pi(.31)^2}{4} =$

Assume

Homogenous
Secure connection to plate
Rigid body
N>3

Method

FBD
I
Y

$$Y = \frac{-PL^3}{3EI} \qquad I = \frac{\pi D^4}{64} = \frac{\pi(.31)^2}{64} = 4.7\times10^{-3}$$

$$Y = \frac{-(150\#)(3)(1.2'')^3}{3(10\times10^6)(4.7\times10^{-3})}$$

$$Y_{max} = -5.5\times10^{-3} = .0055'' \quad \text{ok}$$

For 4130 OQT 1000 $S_y = 132$ ksi $E = 30\times10^6$ psi

$$Y = \frac{-(150)(3)(1.2'')^3}{3(30\times10^6)(4.7\times10^{-3})}$$

$$Y_{max} = .0018'' \quad \text{better}$$

A-7 – Geometry of Main Axles

Geometry of Main Axles | Analysis #7

Given
Length = 8"
Hexagon/square/circular/octagon
1020 CD steel & 5052 Al
$M = 300\#\text{-in}$
1020 CD or 5052 Al
$S_y = 51\text{ksi}$ / $S_y = 31\text{ksi}$

Find
Values for different shapes min. diameters

Assume
Rigid Body
Evenly distributed load

Hexagon

$S = 0.120D^3$

For 1020 CD Steel

$$51000 = \frac{300}{.120D^3}$$

$D = 0.366"$

For 5052 Al

$$31000 = \frac{300}{.120D^3}$$

$D = 0.432"$

Octagon

$S = 0.6381r^3$

For 1020 CD Steel

$$51000 = \frac{300}{.6381r^3}$$

$r = 0.2097"$

$D = 0.419"$

For 5052 Al

$$31000 = \frac{300}{.6381r^3}$$

$r = 0.2475"$

$D = 0.495"$

Square

$$S = \frac{H^3}{6}$$

For 1020 CD steel

$$51000 = \frac{300}{\left(\frac{H^3}{6}\right)}$$

$H = 0.328"$

5052 Al

$$31000 = \frac{300}{\left(\frac{H^3}{6}\right)}$$

$H = 0.387"$

Circular

$$S = \frac{\pi D^3}{32}$$

For 1020 CD steel

$$51000 = \frac{300}{\left(\frac{\pi D^3}{32}\right)}$$

$D = 0.391"$

5052 Al

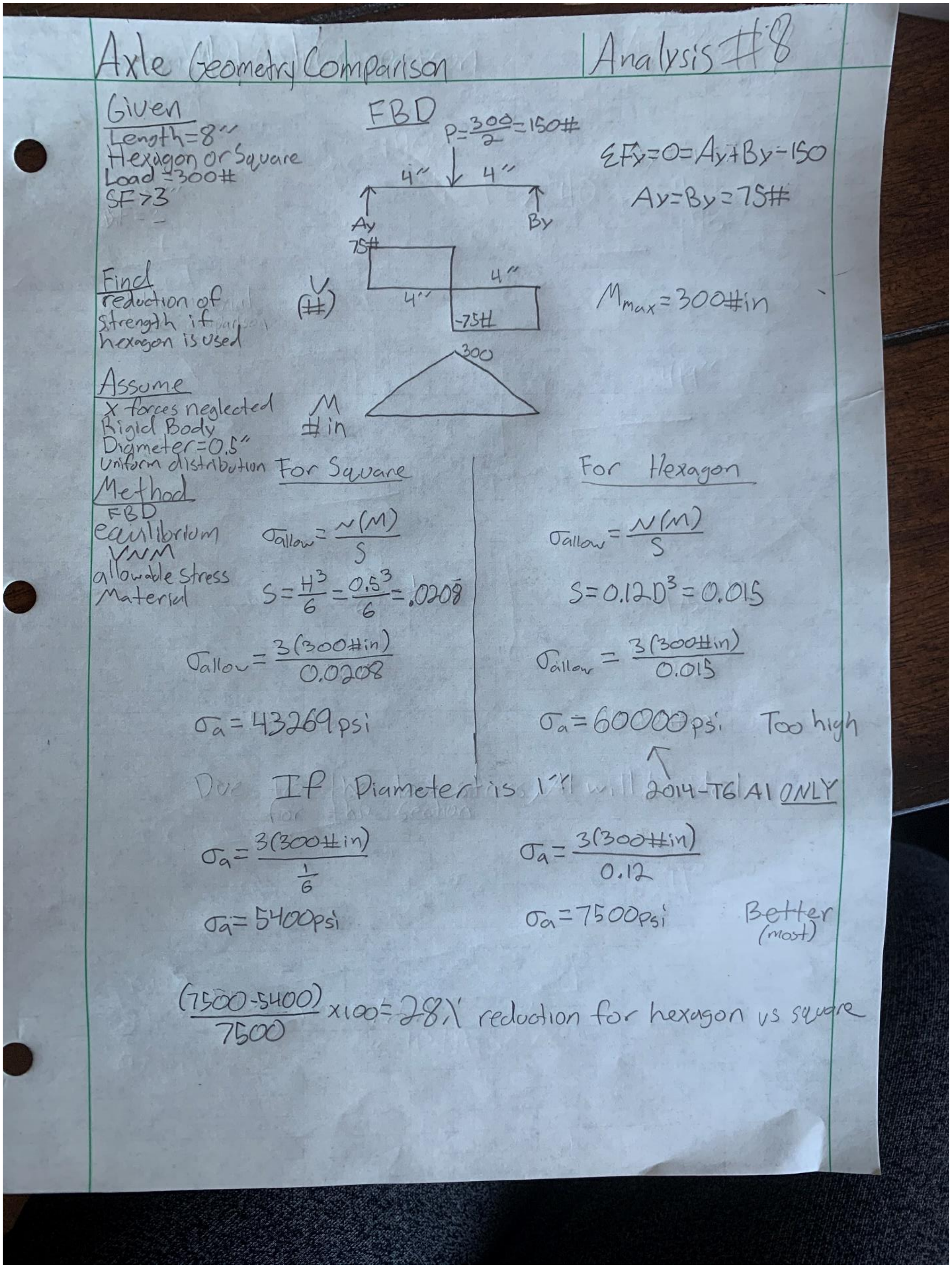
$$31000 = \frac{300}{\left(\frac{\pi D^3}{32}\right)}$$

$D = 0.46"$

COMPARISON

Rank Best to worst:
1. Square
2. Hexagon
3. Circular
4. Octagon

A-8 – Main Axle Geometry Comparison



Axle Geometry Comparison | Analysis #8

Given
Length = 8"
Hexagon or Square
Load = 300#
SF > 3

FBD

$P = \frac{300}{2} = 150\#$

4" 4"

Ay By

75#

4" 4"

-75#

V (#)

300

M #in

$\Sigma F_y = 0 = A_y + B_y - 150$

$A_y = B_y = 75\#$

$M_{max} = 300\#in$

Find
reduction of strength if hexagon is used

Assume
X forces neglected
Rigid Body
Diameter = 0.5"
Uniform distribution

Method
FBD
equilibrium
VNM
allowable stress
Material

For Square

$\sigma_{allow} = \frac{N(M)}{S}$

$S = \frac{H^3}{6} = \frac{0.5^3}{6} = .0208$

$\sigma_{allow} = \frac{3(300\#in)}{0.0208}$

$\sigma_a = 43269\ psi$

For Hexagon

$\sigma_{allow} = \frac{N(M)}{S}$

$S = 0.12D^3 = 0.015$

$\sigma_{allow} = \frac{3(300\#in)}{0.015}$

$\sigma_a = 60000\ psi$ Too high

2014-T6 Al ONLY

If Diameter is 1"

$\sigma_a = \frac{3(300\#in)}{\frac{1}{6}}$

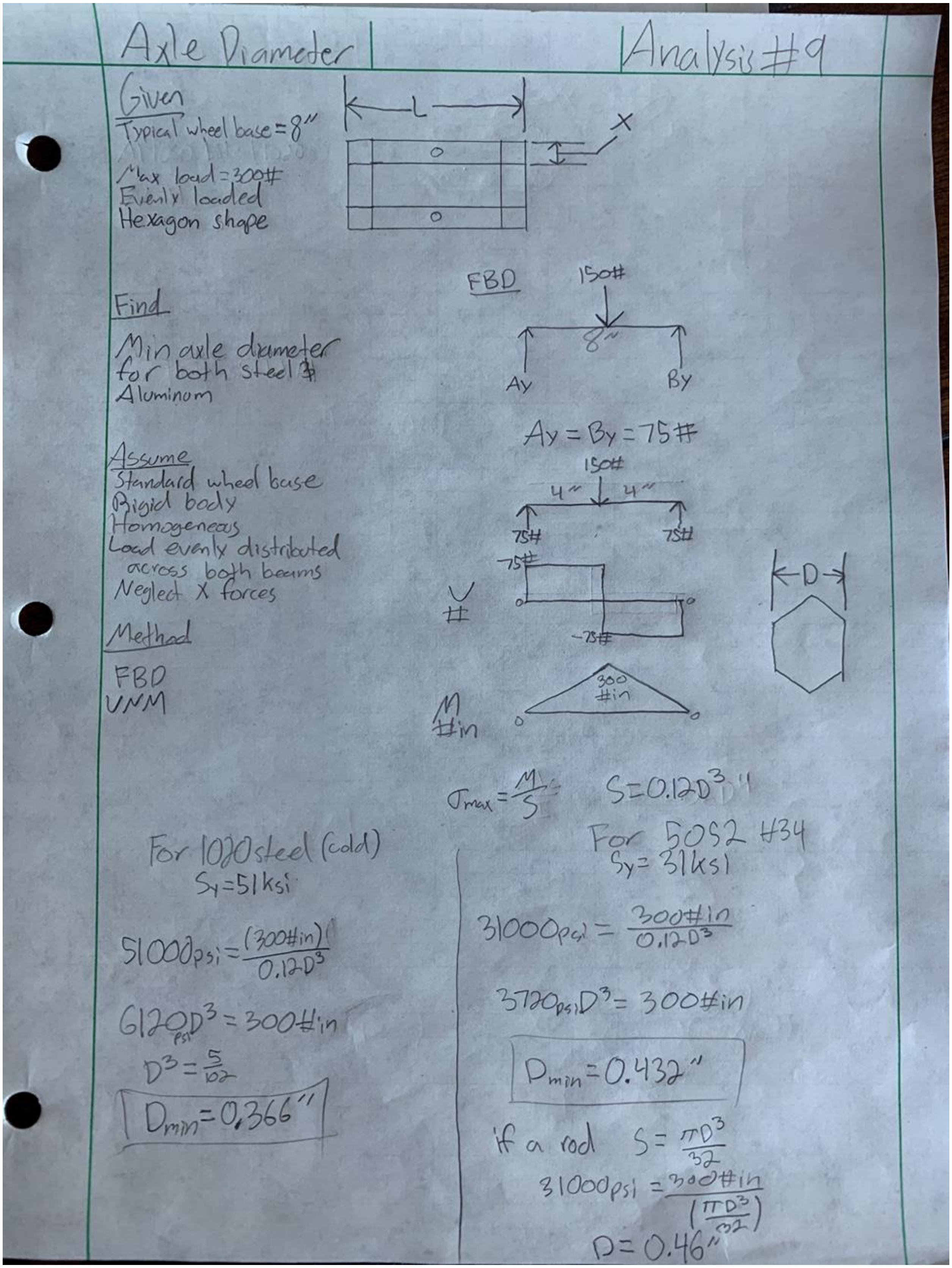
$\sigma_a = 5400\ psi$

$\sigma_a = \frac{3(300\#in)}{0.12}$

$\sigma_a = 7500\ psi$ Better (most)

$\frac{(7500 - 5400)}{7500} \times 100 = 28\%$ reduction for hexagon vs square

A-9 – Diameter of Main Axles



Axle Diameter | Analysis #9

Given

Typical wheel base = 8"

Max load = 300#

Evenly loaded

Hexagon shape

Find

Min axle diameter for both steel & Aluminum

Assume

Standard wheel base

Rigid body

Homogeneous

Load evenly distributed across both beams

Neglect X forces

Method

FBD

UNM

$A_y = B_y = 75\#$

$\sigma_{max} = \frac{M}{S}$ $S = 0.12D^3$

For 1020 steel (cold)

$S_y = 51\,ksi$

$51000\,psi = \frac{(300\#in)}{0.12D^3}$

$6120_{psi} D^3 = 300\#in$

$D^3 = \frac{5}{102}$

$D_{min} = 0.366''$

For 5052 H34

$S_y = 31\,ksi$

$31000\,psi = \frac{300\#in}{0.12D^3}$

$3720_{psi} D^3 = 300\#in$

$D_{min} = 0.432''$

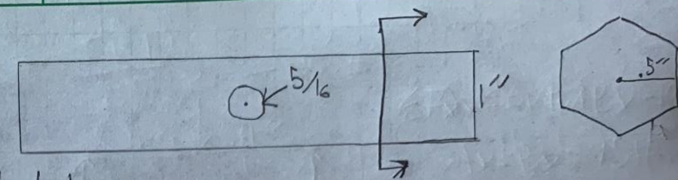
if a rod $S = \frac{\pi D^3}{32}$

$31000\,psi = \frac{300\#in}{\left(\frac{\pi D^3}{32}\right)}$

$D = 0.46''$

A-10 – Material of Main Axle with Stress Check

Axle Stress w/ Pin Holes — Analysis #10



Given
5/16" Pins
8" Length
300# load on 2 axles
5052-H34 Al
Hexagon of 0.87" D

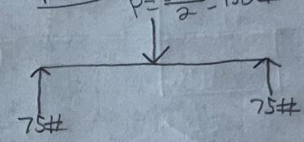
Find
Safety Factor if hexagon is used

Assume
Rigid Body
Uniform load
Stationary

Method
FBD
Min D
σ
N

Solution

FBD



D @ Hole

$$D_{min} = .87 - 5/16" = 0.5575"$$

$$\sigma = \frac{M}{S} \qquad S = 0.12 D^3$$

$$S = 0.12(0.5575")^3 = 0.0208 in^3$$

$$M = 300\#in$$

$$\sigma = \frac{300\#in}{0.0208 in^3} = 14427 psi$$

5052
$S_y = 31000 psi$

$$N = \frac{31000}{14427} = 2.15$$ Hexagon is ok

If $N > 2.5$ Must use 5052-H38
$S_y = 37000$

$$N = \frac{37000}{14427} = 2.56$$

A-11 – Deflection of Main Axle

Deflection of Main Axles | Analysis #11

Given

Typical base = 8"
Max load = 300#
5052 Al
Sy = 31 ksi
2 axles handling load
D = 0.87"
Pin = 5/16"
$E = 10 \times 10^6$ psi

Find

Deflections at center

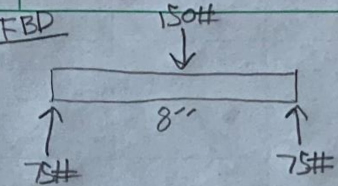
Assume

Homogeneous
Evenly distributed load

Method

FBD
I
y

FBD



$$I = 0.06 D^4$$

hole

$$I = 0.06(0.87'' - 5/16'')^4$$

$$= 5.8 \times 10^{-3}$$

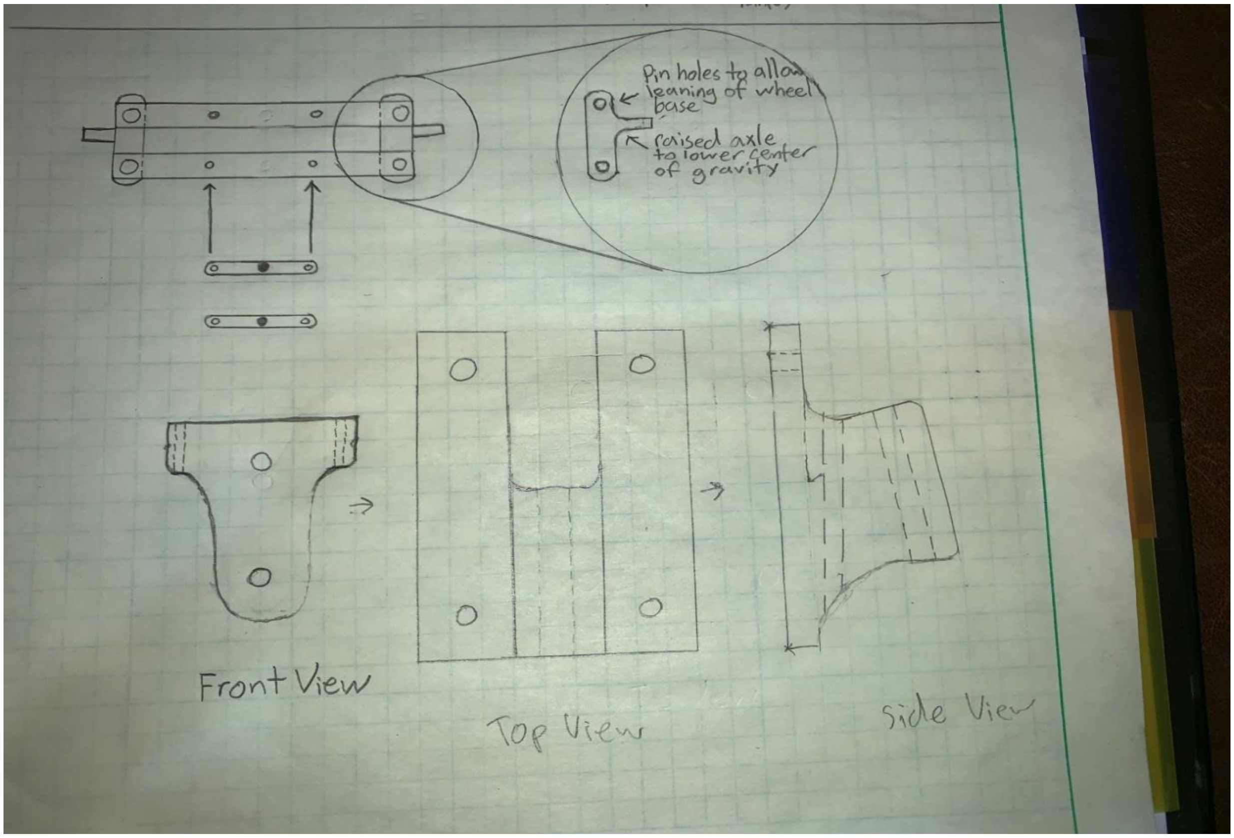
$$Y_{max} = \frac{-PL^3}{48EI}$$

$$= \frac{-150(8'')^3}{48(10 \times 10^6 psi)(5.8 \times 10^{-3})}$$

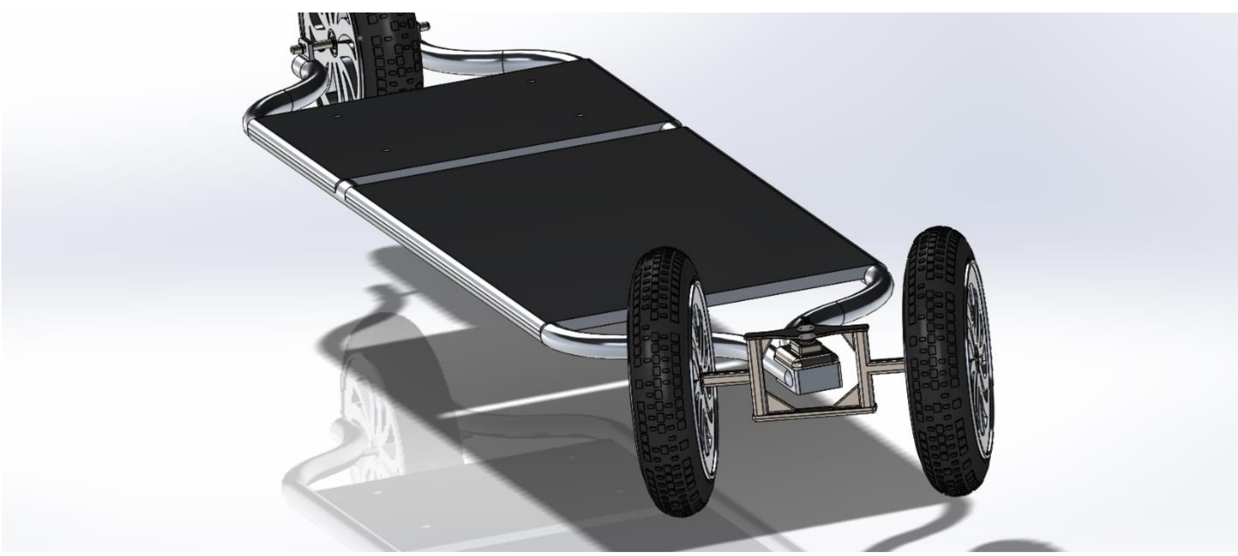
$$= -0.027''$$

Appendix B – Sketches, Drawings

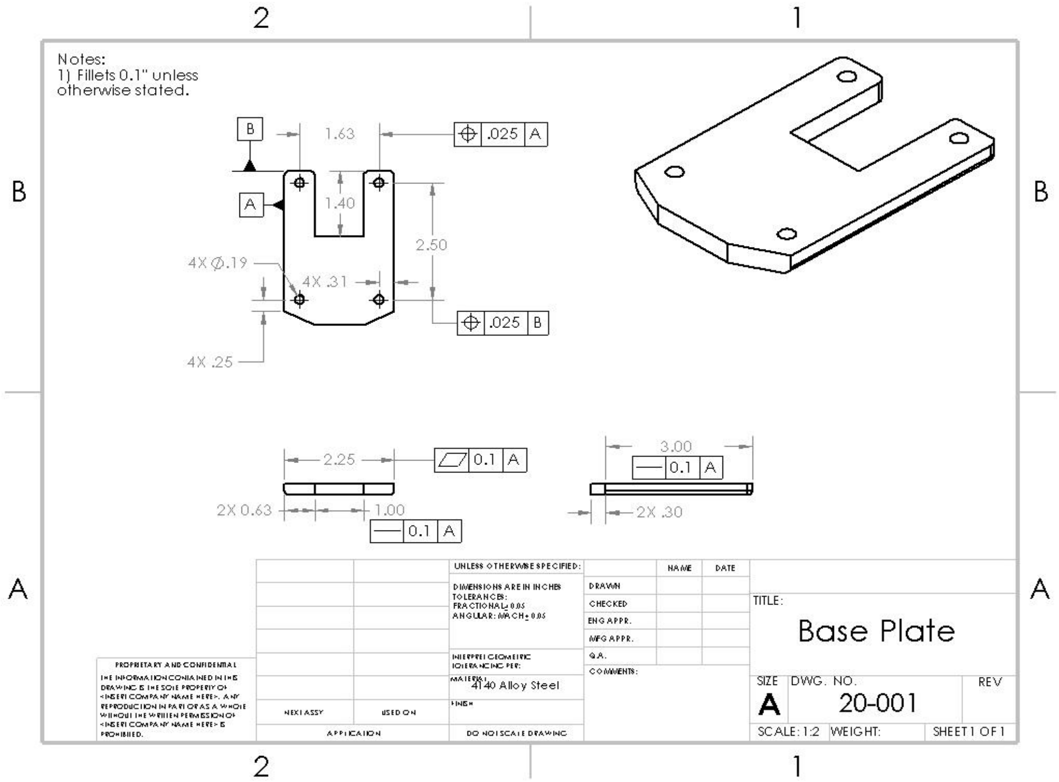
B-1 - Original Sketch



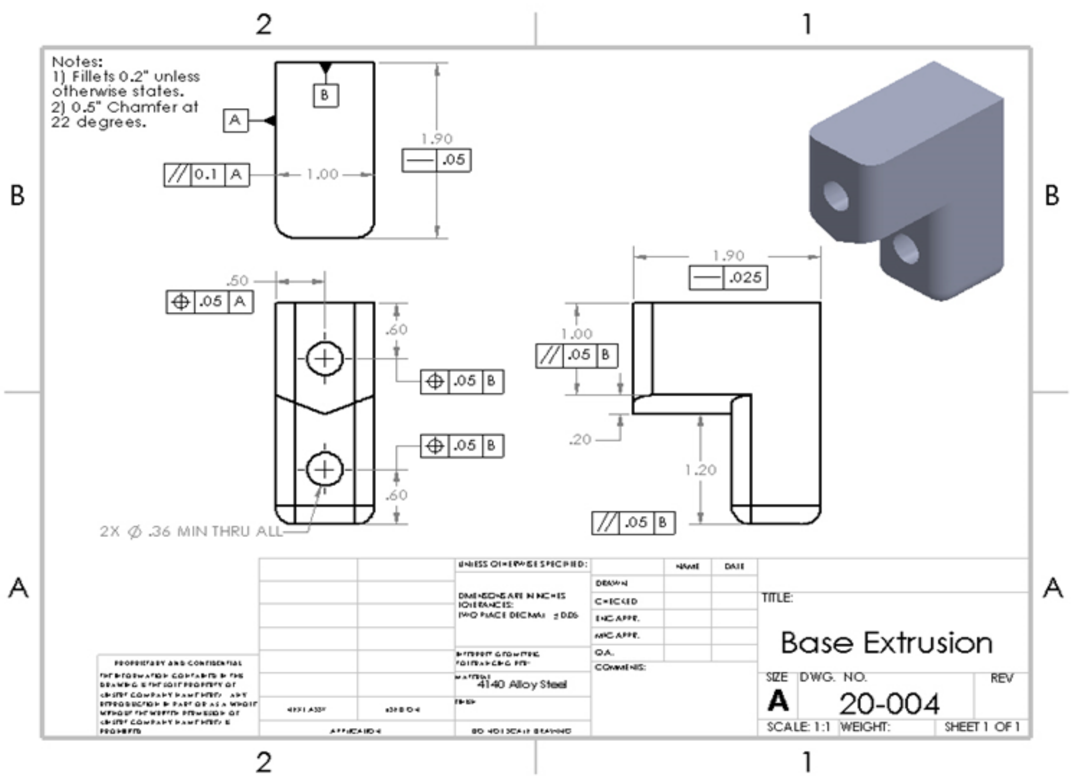
B-2 – Previous Design



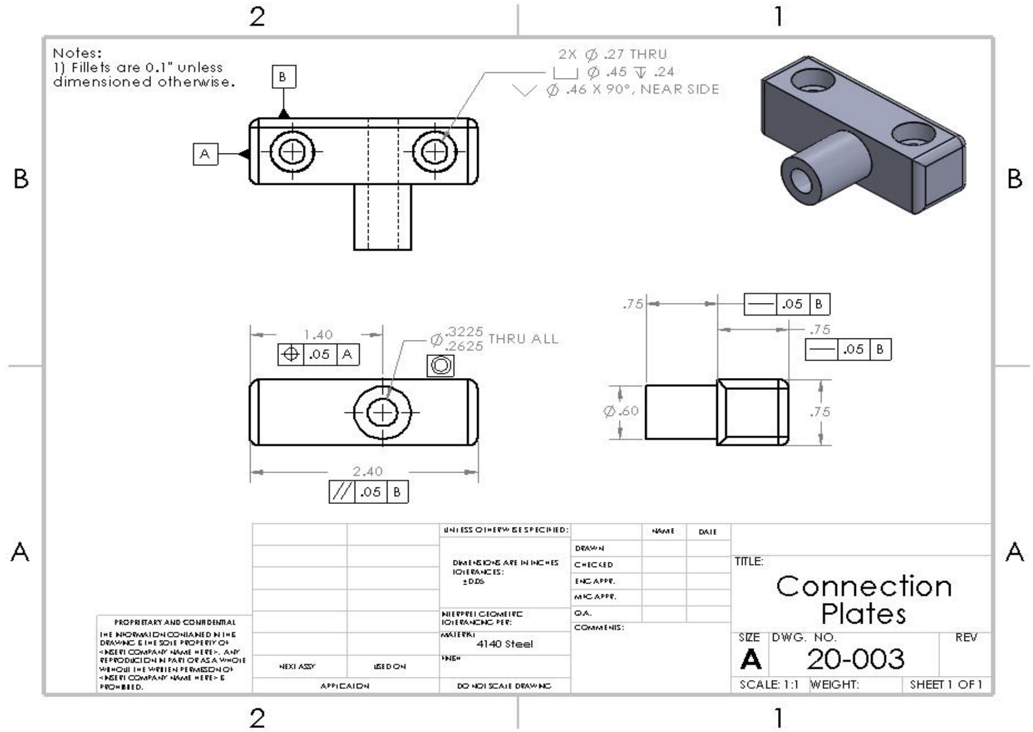
B-3 - 20-001 Truck Base Plate



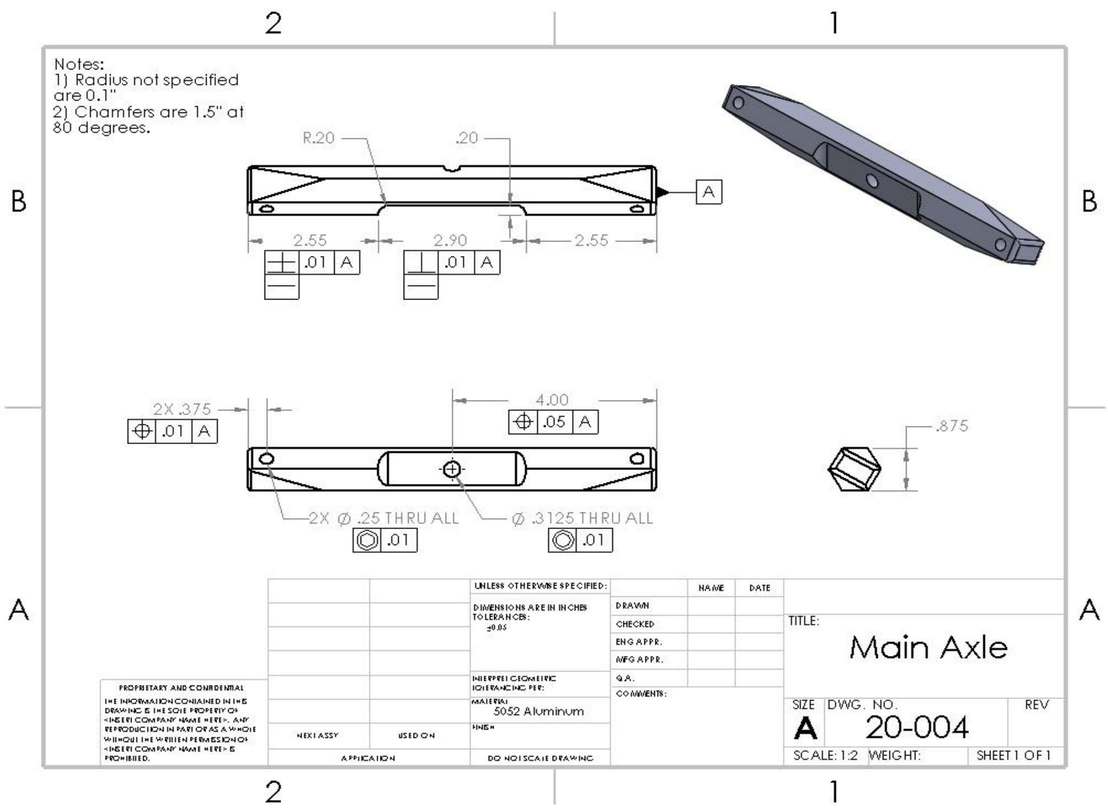
B-4 – 20-002 Base Extrusion



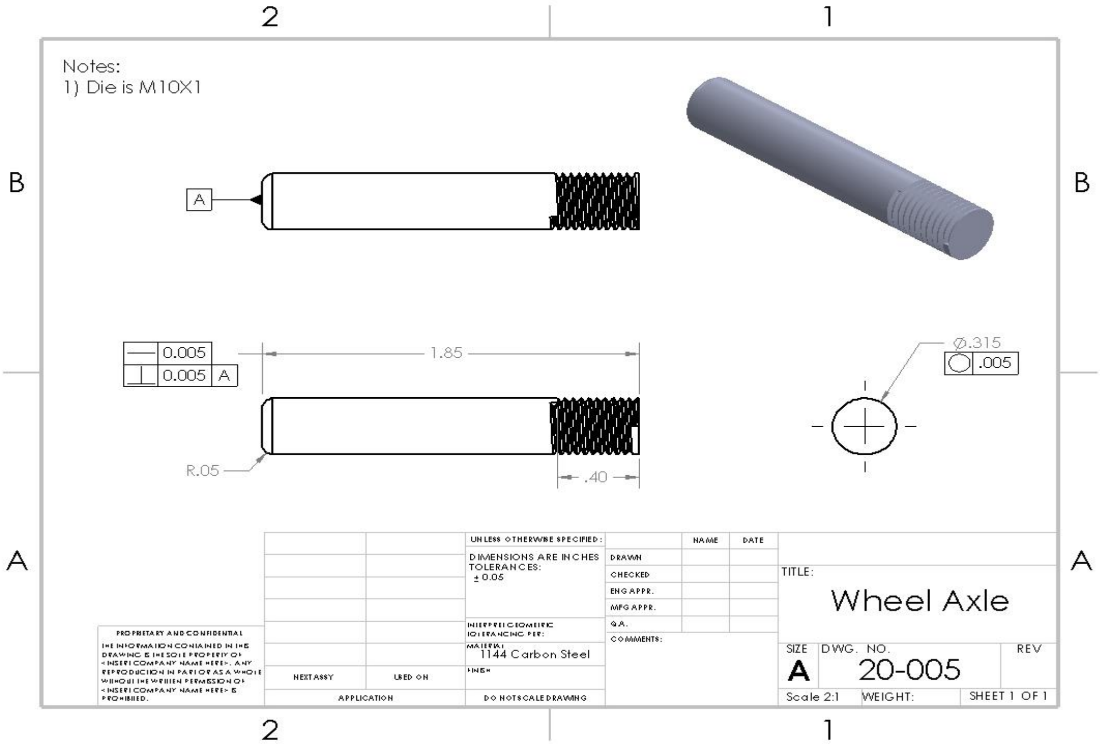
B-5 – 20-003 Connection Plate



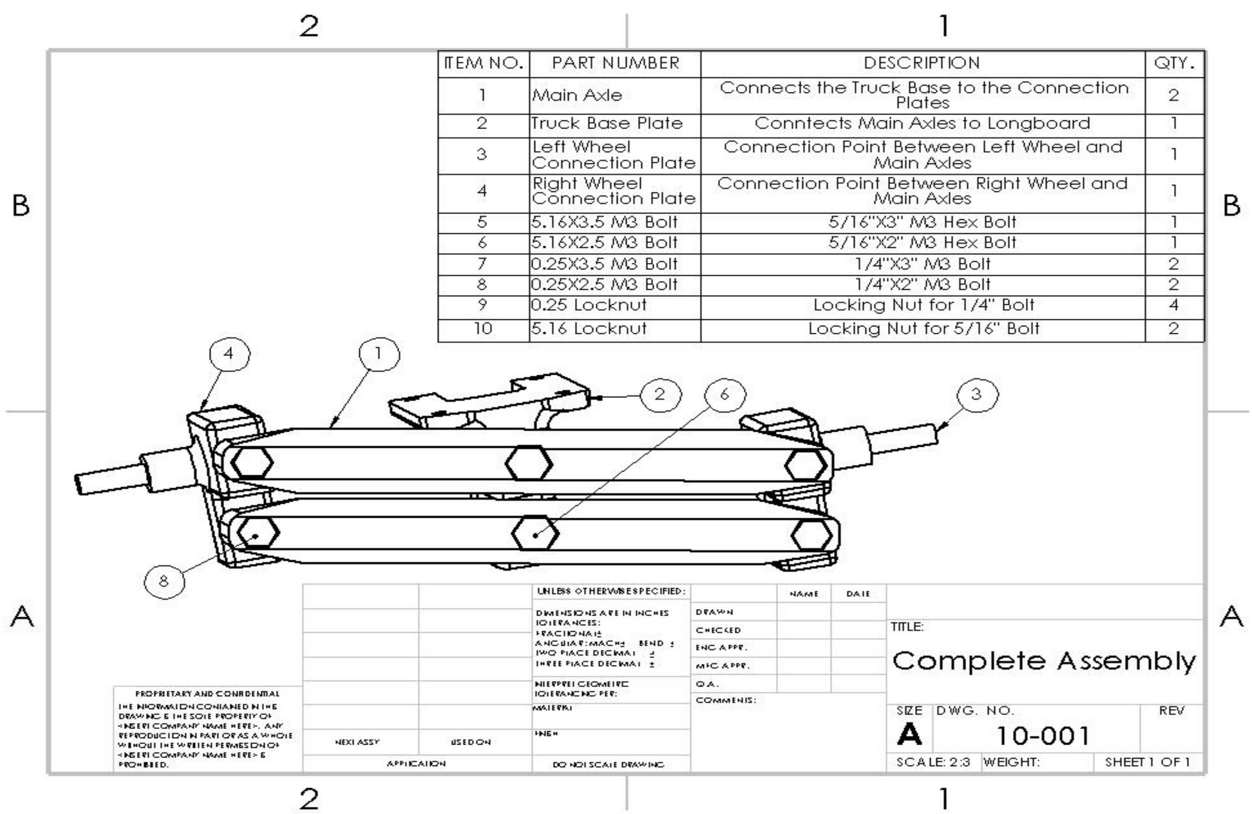
B-6 – 20-004 Main Axle



B-7 – 20-005 Wheel Axle

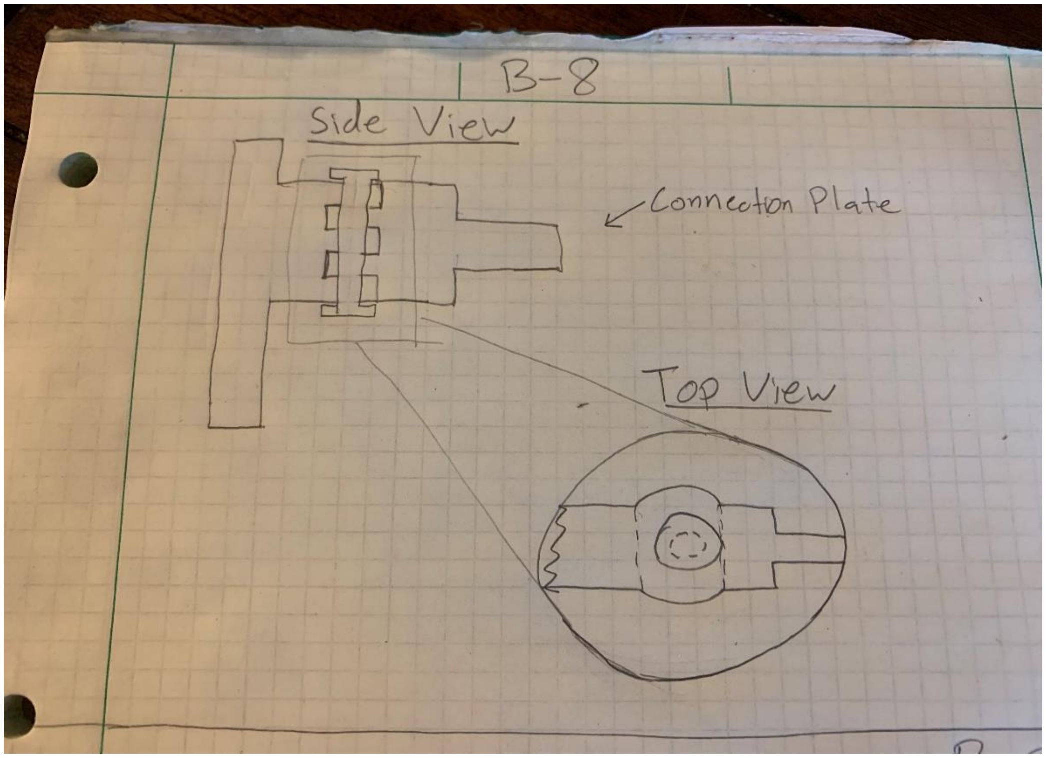


B-8 – 10-001 Complete Assembly

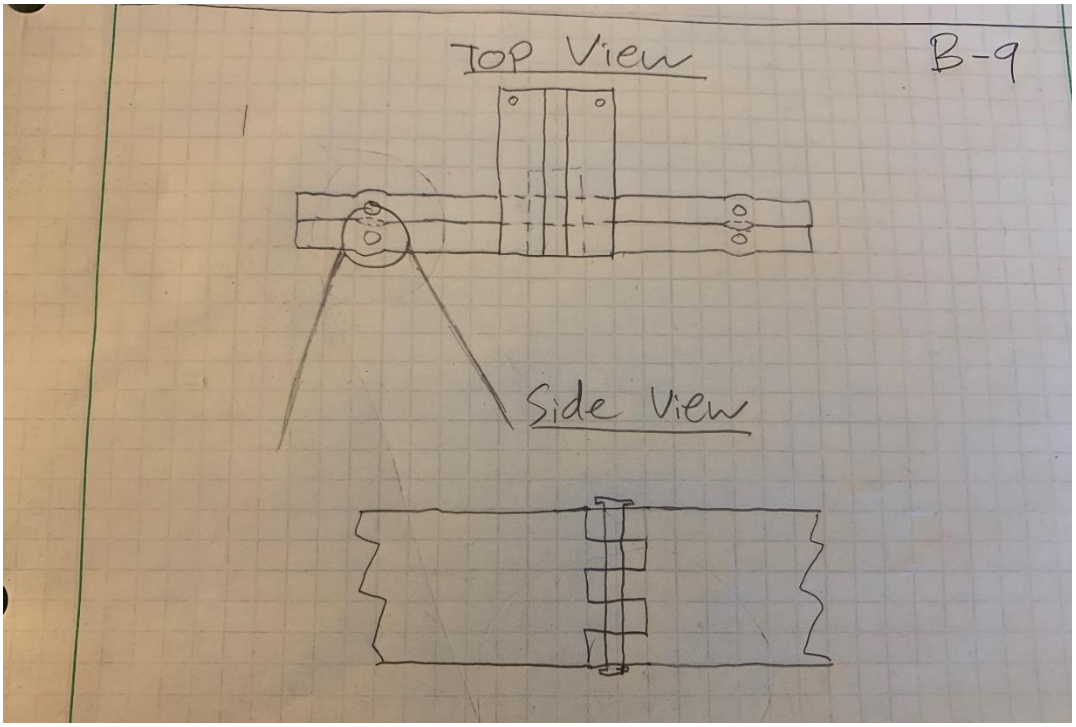


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Main Axle	Connects the Truck Base to the Connection Plates	2
2	Truck Base Plate	Conntects Main Axles to Longboard	1
3	Left Wheel Connection Plate	Connection Point Between Left Wheel and Main Axles	1
4	Right Wheel Connection Plate	Connection Point Between Right Wheel and Main Axles	1
5	5.16X3.5 M3 Bolt	5/16"X3" M3 Hex Bolt	1
6	5.16X2.5 M3 Bolt	5/16"X2" M3 Hex Bolt	1
7	0.25X3.5 M3 Bolt	1/4"X3" M3 Bolt	2
8	0.25X2.5 M3 Bolt	1/4"X2" M3 Bolt	2
9	0.25 Locknut	Locking Nut for 1/4" Bolt	4
10	5.16 Locknut	Locking Nut for 5/16" Bolt	2

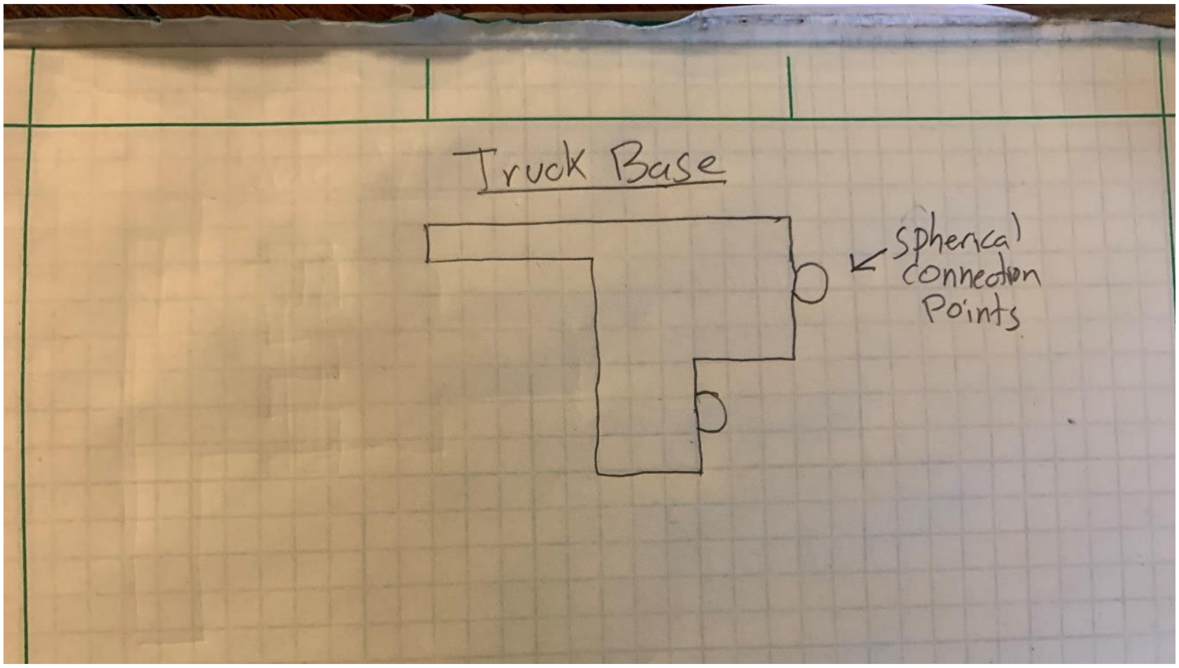
B-9 – Redesign Sketch #1



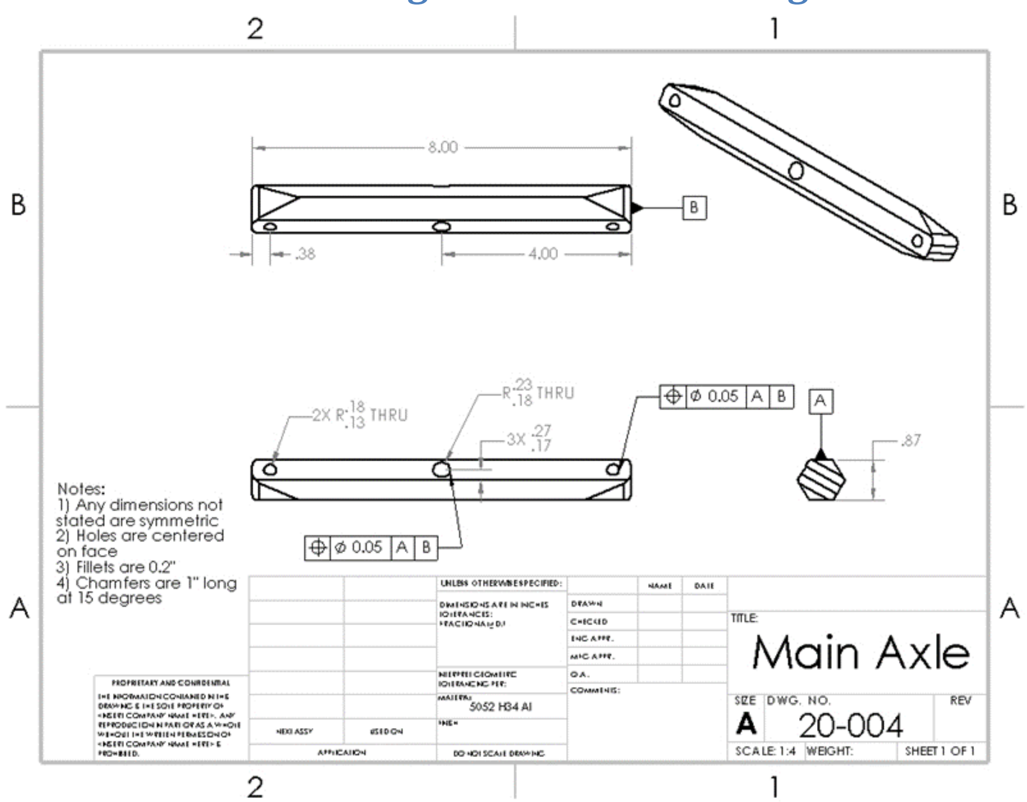
B-10 – Redesign Sketch #2



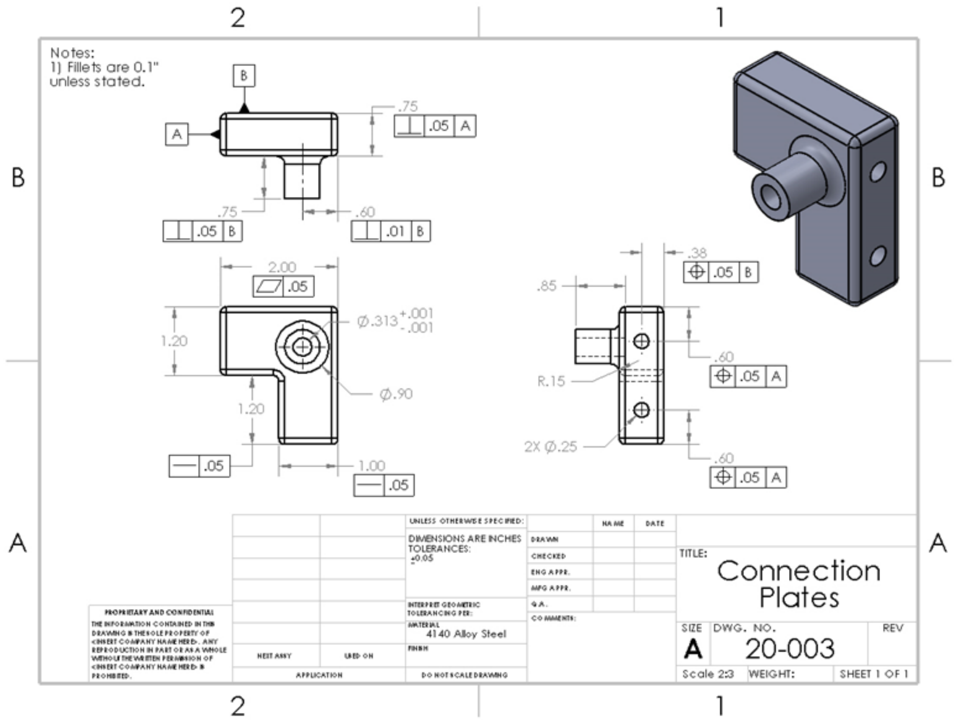
B-11 – Redesign Sketch #3



B-12 – Original Main Axle Design



B-13 – Original Connection Plate Design



Appendix C – Parts List

Parts List		
Part	Description (for)	Quantity
3/8"X3" - 16	Long Truck Pin	2
3/8"X2" - 16	Short Truck Pin	2
1/4"X2" - 20	Axle Pin	8
3/8" - 16	Truck Lock Nuts & Washers	4
1/4" - 20	Axle Lock Nuts & Washers	8
2024 Al Hex Rods	Main Axles	4
4140 Steel Bar	Truck Base Plates	2
4140 Steel Bar	Connection Plates	4
4140 Steel Bar	Base Extrusion	2
1144 Steel Rod	Wheel Axles	4

Appendix D – Budget

D-1 – Cost & Budget

				$/hours	hours/feet	Cost
Item ID	Item Description	Item Source	Size (Purchased)	Price/Cost	Quantity/Length	Subtotals
1	Truck Plates	Fabrication	1/4"Tx2.5"W	$ 17.04	1	$ 17.04
1a	4140 Steel Bar	McMaster Carr				
1b	Plate Fabrication	Shop/Labor		$ 15.00	3.1	$ 46.50
2	Truck Extrusion	Fabrication	1"Tx2.5"W	$ 33.70	0.5	$ 33.70
2a	4140 Steel Bar	McMaster Carr				
2b	Extrusion Fabrication	Shop/Labor		$ 15.00	6.3	$ 94.50
3	Main Axles	Fabrication	7/8"W	$ 44.89	3	$ 44.89
3a	2024 Alum. Hex Rod	McMaster Carr				
3b	Axle Fabrication	Shop/Labor		$ 15.00	5.3	$ 79.50
4	Wheel Axles	Fabrication	8mm Dia.	$ 10.31	3	$ 10.31
4a	1144 Steel Rod	McMaster Carr				
4b	Axle Fabrication	Shop/Labor		$ 15.00	3.4	$ 51.00
5	Connection Plates	Fabrication	1.5Tx2.5W	$ 78.09	1	$ 78.09
5a	4140 Steel Bar	McMaster Carr				
5b	Plate Fabrication	Shop/Labor		$ 15.00	12	$ 180.00
6	Bolts & Nuts	Fastenal	See Below			
6a	Long Truck Pin	Fastenal	3/8"-20 X 3"	$ 0.30	2	$ 0.60
6b	Short Truck Pin	Fastenal	3/8"-20 X 2"	$ 0.30	2	$ 0.60
6c	Plate Pins	Fastenal	1/4"-20 X 2"	$ 0.30	8	$ 2.40
6d	1/4" Lock Nuts	CWU Fastenal	1/4"-20 UNC	$ 0.30	8	$ 2.40
6e	3/8" Lock Nuts	CWU Fastenal	3/8"-20 UNC	$ 0.30	4	$ 1.20
7	Welding Assembly	Fabrication	Spool	$15	1	$ 15.00
7a	Welding Wire	Amazon				
7b	Welding Time	Shop/Labor	N/A	$15	4.2	$ 63.00
6a	Assembly Time	Labor	N/A	$15	2	$ 30.00
					Totals	$ 750.73
					Excluding Labor	$ 206.23

Appendix E – Schedule

E-1 – Gantt Chart

Description	Duration Est. (hrs)	Actual (hrs)	%Comp	S	October				November				Dec		January				February				March				April				May				June	
CT TITLE: Geo-Trucks																																				
al Investigator.: Zach Ducatt																																				
FALL QUARTER																																				
Proposal*																																				
Outline	1	1		X	X																															
Intro	1	2				X																														
Methods	2	3					X																													
Analysis	5	15				X	X	X	X	X	X	X	X																							
Discussion	3	5										X	X																							
Parts and Budget	1	2							X																											
Drawings	4	5							X	X	X																									
Schedule	1	3								X	X																									
Summary & Appx	5	8						X	X	X	X	X	X																							
subtotal:	23	44																																		
Analyses																																				
Pin Diameters	1	1			X																															
Axle Pin Diameter	1	2				X																														
Connection Axle Deflection	1	1					X																													
Wheel Deflection	1	2						X																												
Base Axle Diameter	1	1							X																											
Base Axle Stress	1	1								X																										
Axle Extrusion	1	1									X																									
Connection Plate Material	1	2										X																								
subtotal:	8	11																																		
				S	October				November				Dec		January				February				March				April				May				June	
Documentation																																				
Truck Base Drawing	1	2							X																											
Axle Drawing	1	2								X																										
Subassembly Base	2	2										X																								
Left Connection Plate Drawing	1	2								X																										
Right Connection Plate Drawing	1	1							X																											
Assembly Connection Plates	2	2										X																								
Device Assembled Drawing	2	3											X																							
Kinematic Check/Analysis	3	4										X	X	X	X	X	X																			
Meet ANSIY14.5 Guidelines	4	5									X	X																								
Make Object Files	1	1													X	X																				
subtotal:	18	24																																		
Proposal & Design Mods																																				
Axle Shape Change to Octagon	2	2									X	X																								
Additional Swivel for Turning	2	6													X	X	X	X																		
Critical Design Review	2	4												X	X	X																				
Editing	4	4			X					X	X	X				X	X	X																		
subtotal:	10	16																																		
WINTER QUARTER																																				
Part Construction																																				
Truck Base	2	3																																		
Main Axles (x2)	2	4																																		
Left Connection Plate	3	2																																		
Right Connection Plate	3	3																																		
Truck Base	1	2																																		
Main Axles (x2)	2	2																																		
Left Connection Plate	2	2																																		
Right Connection Plate	2	2																																		
Update Website	2	3																																		
Manufacture Plan	1	1																																		
subtotal:	20	24																																		
				S	October				November				Dec		January				February				March				April				May				June	
Device Construct																																				
Sub Assembly A	1	0.5																																		
Sub Assembly B	1	0.5																																		
Sub Assembly C	1	0.5																																		
Second Geo-Truck	2	1																																		
Board Attachment	2	1																																		
Take Device Pictures	1	1																																		
Update Website	2	3																																		
subtotal:	10	7.5																																		

Appendix J – Job Hazard Analysis

J-1 – Job Hazard Analysis

JOB HAZARD ANALYSIS
NG Trucks

Prepared by: Zach Ducatt	Reviewed by: Approved by:

Location of Task:	Central Washington University, Home
Required Equipment / Training for Task:	Training with machining lab and equipment such as drill press, lathe, mill. 3-D printer safety awareness, heat, abrasive material
Reference Materials as appropriate:	Principle Engineer’s Engineering Notebook

Personal Protective Equipment (PPE) Required (Check the box for required PPE and list any additional/specific PPE to be used in “Controls” section)						
Gloves	Dust Mask	Eye Protection	Welding Mask	Appropriate Footwear	Hearing Protection	Protective Clothing
☒	☒	☒	☒	☒	☒	☒
Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.						

	TASK DESCRIPTION	HAZARDS	CONTROLS
	Drill Press	**Flying Chips Rotating Parts Cuts Slip, trip, fall Pinch points Posture**	**Training for the Drill Press, PPE including eye protection. Ensure material is in vise and clamped securely. Ensure PPE is worn. Ensure area is clear of all tripping hazards. Be aware of hand and finger location at all times. Rotate job tasks when possible. Ensure table is at proper ergonomic level.**

			Wear gloves.
	Welding	Inhalation. Burn, fire. Burns. Welder's flash. Burns / heat. Awkward position.	Ensure PPE is worn. Work in welding hood. Protect job site with barriers/curtains. Ensure ventilation is adequate for work. Ensure PPE is worn. Wear cotton long sleeved shirt and appropriate PPE. Change / rotate positions when possible.
	Milling and Lathe Machines .	Injury to hands from milling blades. Hearing damage from noise of machine operation. Possible eye injury from wire stitches thrown out by milling blade. Crushing finger hazard from book clamp. Cuts from moving mill bits. Spinning machinery hazard.	Wear safety glasses during operation. Wear hearing protection, such as ear plugs, if operating machine for periods extending more than 10 minutes. Never disconnect safety shields from milling blades. Avoid moving mill bit, turn machine off when adjusting or measuring parts. Ensure no tripping hazards around working area. Short sleeve shirts only.
	Hand Tools	Lacerations, pinching or impact. Injuries to self and others.	Ensure that the blade is not exposed when transporting. Do not throw the tool. Assess surrounding environment and be aware of others. Avoid contact with blade or teeth of a tool. Be aware of what may happen if the tool slips or is misdirected. Use caution when using a hand tool.
	Finishing Parts in Sanding / Grinding Room	Lacerations and eye damage from flying glass and ground bits. Inhalation of fine dust particles. Burns caused by heat from friction and machine operation.	Wear appropriate gloves and safety glasses. Wear a dust mask. Stand off to the side of the grinder when turning it on. Keep fingers and hands away from moving machinery. Confirm wheels are not

		Flying sparks and debris. Broken pieces of wheels striking operator.	**cracked or broken. Adjust and tighten tool rests / guards. Don’t hold sharp edges. Control amount of pressure exerted on belt and maintain balance. Make sure belt guards are in place.**
	Bandsaw	**Pinching / Cutting Fingers or hands. Flying Debris.**	**Keep fingers and hands away from pinch points. Wear safety glasses. Avoid pinch points between guard and housing and between guard and material. Keep fingers and hands away from blade. Use push bar for smaller materials.**

Appendix H – Test Report

Introduction

The success of the device was gauged by comparing its performance to two other skateboard truck designs that were easily acquired for the project. Failure to meet the set requirements indicates the design does not outperform the trucks that are commonly used today and is unlikely to sell to distributors. This would necessitate a change to the design to correct performance issues.

The NG-Trucks were tested alongside two different types of standard longboard trucks typically used today, reference Appendix A-3. Each of the longboard set-ups will be tested using the same pair of 100mm oversized wheels on the same board deck for consistency. These tests are intended to provide a comparison between the new design of this project to the Reverse Kingpin and Traditional Kingpin Trucks commonly seen today. This comparison will assist in creating future buying potential with a visual helping to explain on how the NG-Trucks have improved upon the original design. The requirements for this project can be referenced below, alongside a brief explanation. The procedure below may be referenced for more in-depth descriptions of the testing process.

8) Must weigh less than 5 lbs. each

- This is a straight-forward requirement. It is tested using a scale to the tenth of a pound and indicates the weight of one truck without the wheels assembled. This data is important to gauge how much weight you will be adding with this design compared to the competitors.

9) Fit a 100mm diameter with a clearance of at least an inch
    - In order to be successful, the trucks must be able to fit oversized wheels to provide a smoother ride. This is tested by measuring the smallest distance between a wheel and board at a maximum turning position with a tape measure. This, along with the next requirement, is used to exhibit one of the main differences between the NG-Trucks and standard trucks- the stability they offer when combined with oversized wheels.
10) Center of gravity no higher than 4 inches off the ground when unloaded
    - This will be measured by finding the distance between the bottom of the assembled board and the ground using a tape measure. This data will be used to show the how spread out your weight is on each truck. The data will be placed over a picture of the longboard to create a rectangle to represent the actual surface area the ride weight is spread out. This will be represented as in^2 along with a visual, seen in Appendix A-6 and A-5.
11) A maximum turning radius of 6 feet
    - The turning radius was found by laying out a grid consisting of 1' x 1' squares directly below a camera and filming a set of trials using the board over the grid at a maximum turn. The grid was constructed using painter’s tape and a tape measure and movements were filmed by a camera placed on a rod positioned above the grid. The data gathered here provides the best visual for comparison of the NG-Trucks to the original trucks in regard to its turning ability.
12) Product must be weather resistant
    - In order to attract any customers, the product must be finalized by being sent to a paint shop so no rusting or corrosion will occur.
13) Able to withstand a 300 lb. load directly above truck
    - A 300 pound load was placed directly above a stationary truck to check the maximum deflection. This is important so that there is no scraping of the trucks on the ground, which would deem the project useless. The data gathered here will show costumers the durability of the trucks.
14) Allow sharp and controlled turns
    - This is the most important requirement and will indicate whether the NG-Trucks are a superior product. The maneuverability is tested on a set of three courses on a sloped sidewalk. Various sections of the sidewalk from Hogue Hall going towards the SURC at Central Washington University were used for this. The courses are described further in the beginning of the testing procedure.

The testing portion of this project took place in the spring quarter of the 2020 school year. Referenced in Appendix A1, this was between the months of March and June. During the first portion of the quarter, the testing was planned and conducted. The middle of the quarter was used to analyze and compare the testing results and preparation period, followed by a presentation period towards the end where this project was displayed.

Method/Approach

In order to begin conducting the testing for this project, materials had to be collected and testing areas had to be constructed. The materials needed consisted of painter's tape, a tape measure, a camera, Traditional Kingpin Trucks, Reverse Kingpin Trucks, and a set of 100mm wheels. Most of these items were readily available, excluding the tape and wheels, which ended up costing $48.00, seen in Appendix A-2. A special thanks goes out to Matt Schrenk and Samuel Cheney for providing their trucks for the testing process. The testing courses were set up in between the Hogue and SURC buildings at Central Washington University. Setting up these courses took about two hours and this process is seen in the first two steps of the testing procedure.

The requirements listed in the introduction of this proposal account for the weight, center of gravity, turning radius, loading, and overall control. Each design was graded by the following methods in order to assess the success of the NG-Truck. The tests were conducted in a controlled and repeatable environment to ensure collection of reliable data. The maneuverability of this design was tested on a grid outlined with tape and equidistance between each line. This grid was directly below a recording camera to give accurate measurements of the testing area. A series of volunteers have ranked the different truck designs on unique terrain areas to gain the final value. Once the data in the testing procedure below is gathered it will be compared with a combination of graphs and images.

The NG-Trucks were engineered to extend the center of gravity's area to 438 square inches while maintaining a tight turning radius of just 6 feet. The trucks were designed to have a safety factor of at least three yet managed to yield a result well above 100 in some places, showing no visual displacement at the 300 lb. maximum load. This allows for further optimization of the weight requirement that was just barely met of five pounds. This design was able to lower the ride height by an average of 17% or 0.85 inches compared to the competitors with oversized wheels. Additionally, the design further allows a decrease in the ride height if a larger wheel was made for the trucks due to the trucks allowing assembly in four different ways. With 100mm wheels being the only sets readily available on the market, the trucks have to be set at their highest setting in order to provide enough clearance below the board. It is estimated that the design can handle wheels as large as a small bicycle.

Test Procedure

When testing this project, at least six hours should be available in order to allow time for set up of the testing area, conduction of each test for the three separate truck designs, and assembly/disassembly of the longboard multiple times. The data used for this project was gathered both in the open lobby of Hogue at Central Washington University along with the sidewalks surrounding this building. The lobby area is used to test weight, center of gravity, loading, and the turning radius of each setup along with all assemblies. The surrounding areas of the building will be used to put comparable numerical data on the maneuverability, stability, and ride comfort. These tests should be conducted on the same day to eliminate variability in weather.

In order to complete these tests, the needed resources include a tape measure, painter's tape, cones or similar object, scale capable of measuring to the 1/10th pound, tools for assembly, and a recording device that can be placed directly above the grid area. Additionally, the NG-Trucks and two different normal trucks (see appendix A-3), one standard longboard deck, and a set of oversized 100mm wheels are required.

Safety exercises were taken referenced in Appendix A-7.

Step1: Use tape measure and painter's tape to lay a 15' x 15' grid below a video camera outlined with 1' squares inside the grid.

Step 2: Outline the outside course with cones or more tape. This must consist of a turn at a high speed (Course 1), cones placed four feet apart in a line on a downhill surface (Course 2), and a steep downhill surface with cones in a slalom style with 15 feet of lateral movement every 30 feet of forwards movement (Course 3).

Step 3: The weight of a single truck is taken before the longboard is assembled. This is tested on a scale to one tenth of a pound. Record value in table provided below.

Step 4: From this point on, a complete longboard setup with two trucks is tested. Assemble the two trucks upon the longboard. Attach the 100mm wheels.

Step 5: The center of gravity is measured with three distances. The first is the height of the bottom surface of the longboard, *Height*. The second is the distance between the center of the front wheels to the center of the rear wheels, *Distance 1*. The third is the distance between the center of the wheels on the same axle, *Distance 2*. Record these values in the table provided below.

Step 6: The turning radius is gathered upon the grid mentioned previously. Record a video of three 180^{o} turns riding over the grid as tight at the trucks will turn. Reference back to the video and use the grid to fill in the table.

Step 7: A 300-pound load is tested by standing directly above the truck with additional weight. This is recorded as a pass or fail in the table. Note any deflections or discrepancies upon the truck.

Step 8: To compare the maneuverability, rank the truck set on a scale from 1-5 (worst-best) on each of the three courses. Add any additional notes on ride quality in the table as well to compare results later. A guideline has also been provided in the appendix to help fathom the scale.

Step 9: Repeat steps 3-8 for the remaining two truck types.

Deliverables

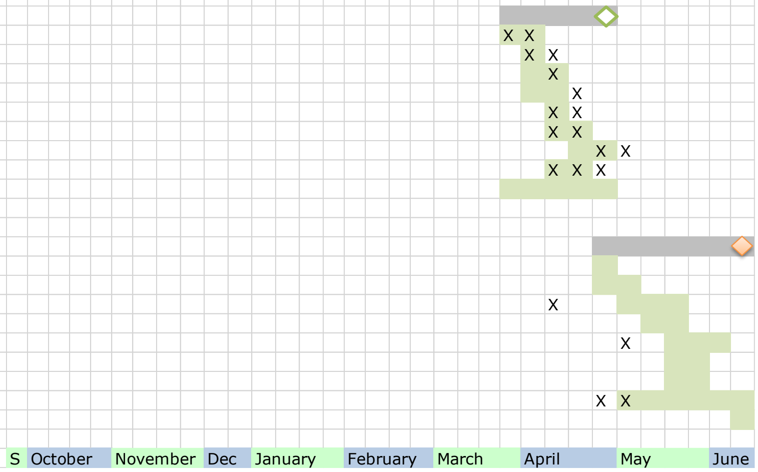
A successful design was specifically engineered to account for the physical style differences between skateboarding and longboarding and does not sacrifice any weight while still improving maneuverability and control of the board during cruising and speed riding styles. The center of gravity was able to be spread out by an average of 36%, providing a more comfortable, stable ride. Further enhancing the ride, the turning radius was able to exceed the expected maximum turning radius of six feet by a total five inches. Even with this turning ability, riders noted that they had almost no feeling of the board sliding out from under them. This quality is due to the leaning motion the trucks create with cornering. Although the NG-Trucks barely met the five-pound weight requirements and were 47% heavier than the competitors, the design was tested using Inventor to show that there are safety factors over 100 in some places. This shows that many of the steel parts can be made out of a high grade aluminum alloy which will also ease the manufacturing process.

It is important to consider that although these are the results for this set of trucks, results will vary with other sets of Traditional Kingpin Trucks and Reverse Kingpin Trucks. For example, the set of Traditional Kingpin Trucks used in this procedure had quite a narrow wheel base. This brought the wheels much too close to the longboard deck, causing an interference issue due to way the Kingpin design brings the wheels closer to and further from the deck to turn. This interference is the reason for the poor results seen in the testing procedure.

Report Appendix

A-1 – Schedule

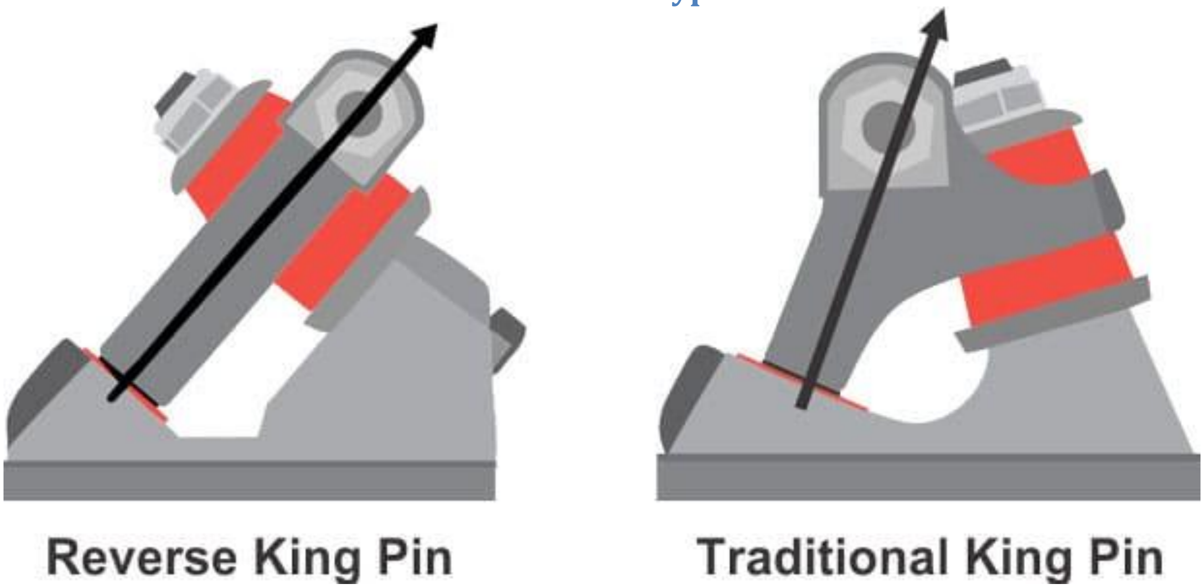
	SPRING QUARTER		
10	Device Evaluation		
10a	List Parameters	1.5	1.5
10b	Design Test&Scope	3.3	2
10c	Obtain resources	2	2.5
10d	Make test sheets	2	2.3
10e	Plan analyses	3	3.2
10f	Test Plan*	6.5	3.5
10g	Perform Evaluation	2.3	1.2
10h	Take Testing Pics	1.5	2.7
10i	Update Website	8	8
	subtotal:	30.1	26.9
11	495 Deliverables		
11a	Get Report Guide	2	2
11b	Make Rep Outline	3.5	3.5
11c	Write Report	1	6
11d	Make Slide Outline	4	4
11e	Create Presentation	4.5	3.8
11f	Make CD Deliv. List	2	2
11g	Write 495 CD parts	1.5	3.8
11h	Update Website	8	8
11i	Project CD*	3	3
	subtotal:	29.5	36.1



A-2 – Cost & Equipment

Item	Price	$ Spent
Tape	$ 3.50	$ 3.50
Measuring Device	$10	$ -
TKP & RKP Trucks	$100	$ -
100mm Wheels	$ 42.00	$ 42.00
Camera	$ 50.00	$ -
Tools	$ 25.00	$ -
Totals	$ 230.50	$ 45.50

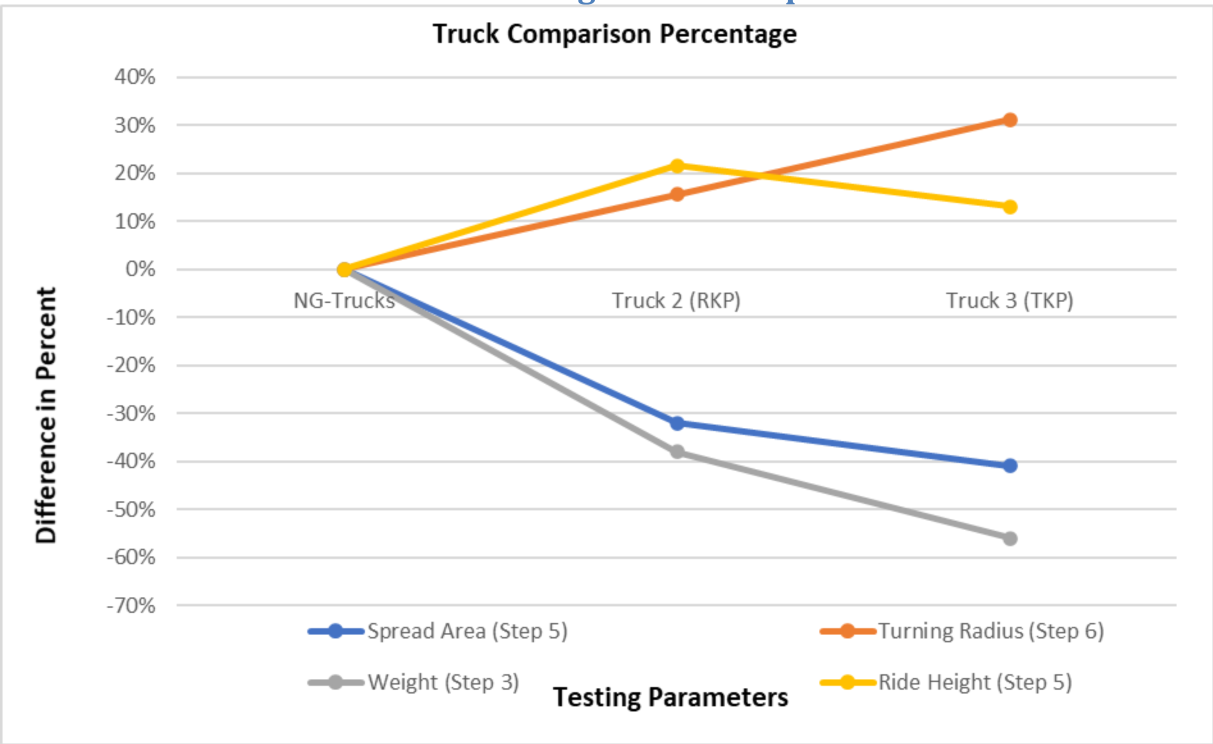
A-3 – Truck Types



A-4 – Testing Procedure Spreadsheet

			NG-Trucks			Truck 2 (RKP)			Truck 3 (TKP)	
Step 3	Weight (lbs)		5.00			3.1			2.2	
	% Difference		0%			-38%			-56%	
Step 5	Height (in)		4.02			5.13			4.62	
	% Difference		0%			21.6%			13%	
	Distance 1 (in)		41.5			36.12			37.12	
	Distance 2 (in)		10.55			8.25			7.00	
	Spread Area (in^2)		438			298			260	
	% Difference		0%			-32%			-41%	
Step 6		Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
	180* Radius (ft)	11.5	11	11.25	13.5	14	12.5	16.25	16.5	16.25
	Average		11.25			13.33			16.33	
	% Difference		0%			15.6%			31.1%	
Step 7	Pass/Fail		Pass			Pass			Pass	
Step 8	Course 1		4			3			3	
	Course 2		5			4			1	
	Course 3		4			4			2	
	Sum		13			11			6	
	% Difference		0%			15.4%			53.9%	
	Notes		The lack of resistance in turning makes it easy to turn too hard and lose balance.			The height increase caused by combination of the large wheels and mounting position of the kingpin causes instability and riding insecurity.			Due to the small wheel base of the Traditional Kingpin Trucks, the large wheels would not allow the trucks to complete their full range of motion.	

A-5 – Testing Results Graph



A-6 – Center of Gravity Spread Image