A Solar Powered Automated Public Transportation System
Full-Scale Drivetrain Team

San Jose State University
Department of Mechanical Engineering
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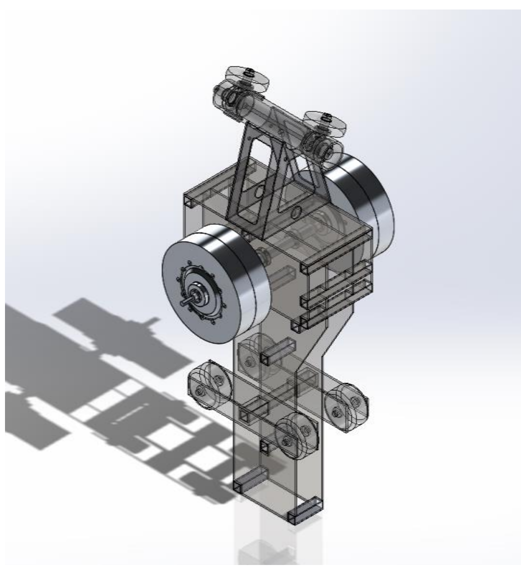

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1.0 Abstract

The Solar Powered Automated Rapid Transport Ascendant Network (SPARTAN) Superway Full-Scale Drivetrain team successfully sourced, retrofitted, and implemented a motor into the drive bogie model. The Full-Scale Drivetrain system consists of two high power density motor, a custom designed motor casing, and a custom designed motor shaft. The motor casing and motor shaft were designed and manufactured to retrofit the sourced motor into one single unit that acted as the wheel system for the drive bogie. The sourced motor is a 24V to 48V brushless direct current hub motor powerful enough to overcome friction force and total payload to drive the whole bogie system forward. The motor casing made of 6061 aluminum that is manufactured into a circular shape that encased the hub motor's original shape. The motor shaft was made of 2024 aluminum and designed to distribute load across the whole Superway system evenly. Face mounted lock collars were also integrated to withstand torque and lateral movement of the shaft within the drive bogie system.

Before sourcing the proper motor for this interdisciplinary project, drivetrain team gathered all requirement set by Dr. Burford J. Furman, Ron Swenson, and other aspect teams. In-Depth, lengthy research, along with reaching out to many electric motor companies was completed to ensure the selected hub motor would meet every requirement set for the drivetrain team. With a caliper and computer-aided design software, a motor casing and shaft was designed to enclose the purchased motor for implementation onto the drive bogie. The designs were 3D printed for test fitting and revisions before the manufacturing process. After the designs were manufactured, they were all combined for implementation.

Although the final design product was not exactly how the drivetrain team envisioned it to be, it was extremely close with minor modifications. However, to further improve on the drivetrain design, a stronger material should be used for the motor shaft, a lock washer should be implemented for torque resistance, and reduce the thickness of the motor casing for weight reduction.

2.0 Acknowledgment

Dr. Burford J. Furman: for this opportunity to work on the first Drivetrain team that focuses on a high-power density motor for SPARTAN Superway. He provided the drivetrain team guidance, supervision, recommendations, and support throughout the decision making and design process.

Ron Swenson: for being Full-Scale Drivetrain's advisor.

Eric Hagstrom: for keeping teams organized, providing feedback, and reminding teams about deadlines.

San Jose State University: for providing an off-campus workspace for manufacturing and prototype testing.

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MakerSpace at San Jose State University: for 3D printing designs for testing and implementation.

Family and friends: for supporting SPARTAN Superway's crowdfunding campaign.

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6.0 Executive Summary

With more vehicles on the road today: traffic congestion, car accidents, and air pollution are the inevitable result. The SPARTAN Superway transportation system is an elevated Automated Transit Network (ATN) that will alleviate these problems. The SPARTAN Superway was created in the hope that the traffic congestions on the streets today will be moved to suspended railways. Additionally, SPARTAN Superway aims to provide on-demand service for the community to encourage more frequent usage of public transportations to reduce carbon footprints emitted by gasoline-powered automobiles. Unlike any other transportation services, SPARTAN Superway relies on solar energy for power. Hence, creating a more fully environmentally friendly mode of transportation.

For the 2018-2019 academic school year, the full-scale prototype went under some very drastic changes. Instead of a single four-wheel bogie, the Superway team decided to go with a two-bogie system; a drive bogie with two wheels and a slave bogie with four wheels. This is to make the bogie system more modular by allowing multiple slave bogies to be powered by a single drive bogie. The drive bogie has two wheels to save space and make the design more compact, while the slave bogie has four wheels for added stability. A new guideway is also currently being designed with a third rail between the tracks.

The drivetrain team's place in these changes is in improving the propulsion system. For the new drive bogie, it was decided that the drive bogie would have two brushless high-power density hub motors to act as it is wheels. Hub motors are ideal in this application because they are easy to service, readily available, compact design, and provide high torque options at low RPMs. To implement a hub motor that would meet our operation parameters, the most viable method we found was to source a motor from a manufacturer. The hub motor that we ended up with was the SOFN geared hub motor made by XOFO. This geared hub motor was a perfect fit for the demonstrative purposes of SPARTAN Superway operating at low speed with high torque requirements.

The hub motors we selected did not fit the design specifications we had in terms of size and shape, so we decided to design and manufacture casings to fit over the motors so they can be used as wheels. The casings were machined with 6061 aluminum, is 10 inches in diameter. We had to first 3D print prototypes for test-fitting, and from that we realized that we had to fix our tolerances. The cases that came in fit perfectly onto the motors and worked well as wheels. Additionally, the team also designed a motor axle that will help the motor to be mounted onto the drive bogie. The axle is a simple tapped rod. We decided to make the rod out of 2024 aluminum, as it's harder than 6061 and therefore can take threads well. However, we realized later that that is not the case, as the threads started stripping if the wheel isn't screwed in at the right orientation. The assembly of the motors, wheels, and axle can be seen in Figure 1.

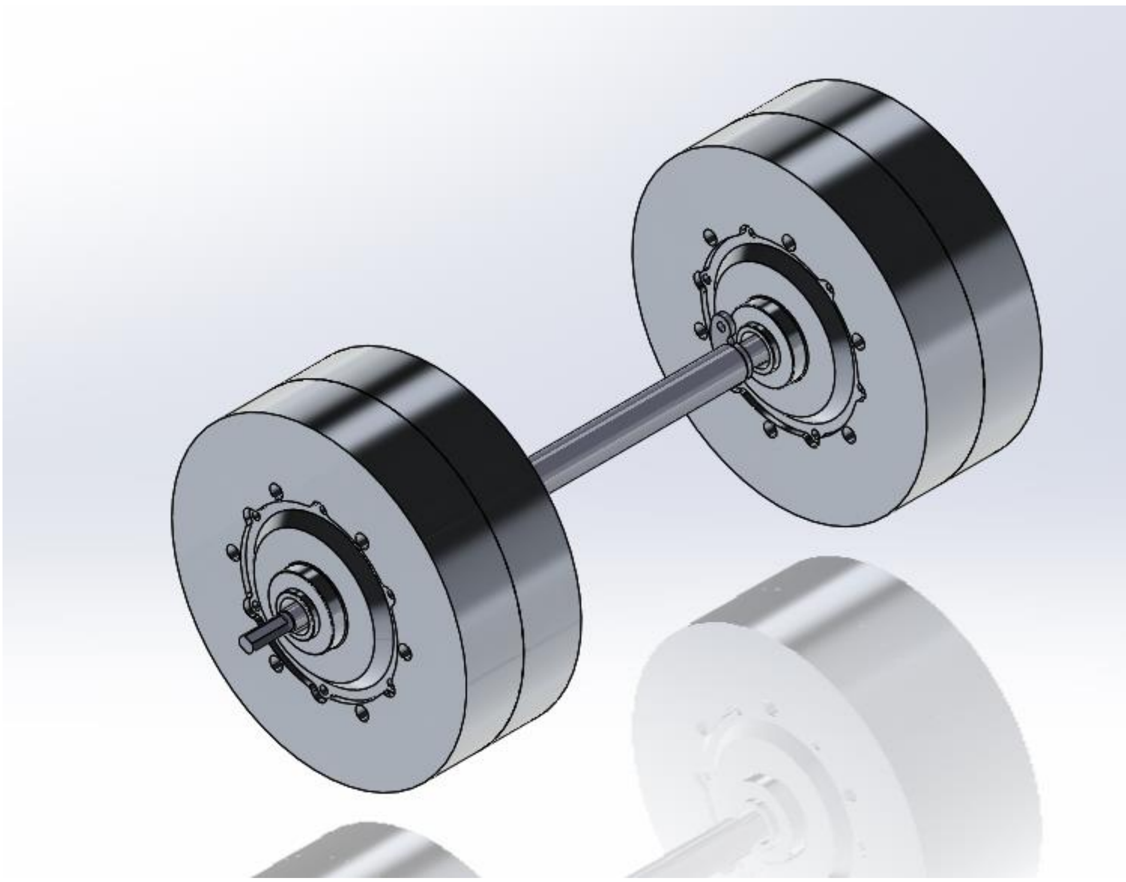

Figure 1: Motors, Wheels, and Axle Assembly

Finally, the team also had to source a compatible motor controller that will help to control the motors. After sizing out the motor, the team found out that not all controllers will be ideal to work along with the team choice of motor. Since the motor will be running at 48 volts and will need a rated current of 15.625 amps, we sourced a motor from Kelly Controls that has a rated voltage of 24 to 48 volts and rated maximum current of 25 amps.

7.0 Introduction

7.1 General Problems that the Community are Facing

The existence of transportation systems has made human's life easier and much more convenient to travel as it gives the flexibility to travel between desired locations promptly. However, there are downsides of having transportation systems. Traveling will be less favorable when there are more vehicles on the road, but transportation emissions are also growing every year. In places such as Silicon Valley, where the number of the population keeps on rising day by day, the number of vehicles on the road will also experience a parallel increase. In 2016, the United States Environmental Protection Agency stated that the most significant source (28 percent) of carbon emission is from transportation. Nevertheless, according to the Association of Bay Area Government, a forecasted total population of the Bay Area, as seen in Figure 2 below, will reach approximately 9.65 million of people by the year 2040.

	2010	2015	2010	2015	2020	2025	2030	2035	2040
Population	7,150,740	7,573,915	7,174,920	7,591,490	7,920,230	8,284,200	8,689,440	9,142,745	9,652,950
Household Population	6,998,465	7,423,305	7,029,350	7,438,280	7,758,540	8,113,640	8,509,245	8,952,495	9,451,375
Households	2,606,290	2,678,810	2,608,025	2,760,480	2,881,965	3,009,055	3,142,015	3,281,130	3,426,700
Persons per Household	2.69	2.77	2.70	2.69	2.69	2.70	2.71	2.73	2.76

Figure 2: Forecasted Total Population of Bay Area

As a result, the number of moving vehicles on the street will drastically increase too. As the number of vehicles on the road increases, there will be several consequences to it. Such consequences include environmental issues of climate change or global warming, as the combustion of gasoline-powered automobiles produces greenhouse gases, which also contributes to the unsustainable environment for the community. In addition, traffic congestions will also be one of the consequences that the Bay Area residents are going to encounter in the future.

7.2 What is an Automated Transit Network?

One of the alternative solutions that can help to overcome the issue of excessive carbon footprints on the atmosphere, as well as traffic congestions in crowded places is to increase the usage of public transport systems. If the number of people commuting by public transports exceeds the number of people commuting by private vehicles, the number of vehicles on the road will drastically decrease, therefore increasing carbon footprints emitted into the atmosphere. Although there are quite a few public transport systems that have already existed in the Bay Area, such as Caltrain and Bart, they do not attract many customers due to the inefficiency in traveling time and convenience. Both transportation services stop at central locations to drop off passengers, and especially during rush hours, these public transportations are packed with passengers commuting, resulting in one's privacy to be disturbed. Hence, a revolutionary form of a public transportation system that is most optimal for the Bay Area is the automated transit network (ATN). In general, ATNs are automated vehicles that provide on-demand services for 24 hours a day, seven days a week. It travels above ground over a specified area to transport a small group of passengers between locations without having to stop at intermediate stops. With that said, commuters no longer must travel with a large group of people or waste more time commuting from places to places. Also, since ATNs travel above ground, it will not increase the traffic congestions of certain crowded places, instead, reducing traffic congestions.

7.3 Societal Impact on SPARTAN Superway

Hence, to address these issues, SPARTAN Superway, an interdisciplinary project from San Jose State University for Silicon Valley was created. SPARTAN Superway, a type of ATN, is designed to provide an environmentally friendly on-demand transportation service that is sustainable, accessible, affordable, safe, and fast for the community. Unlike any other transportation services, SPARTAN Superway is powered by solar power, allowing it to have a zero-emission system, thus sustainable. Not only that SPARTAN Superway positively impact the environment, but it also may increase one's productivity because it reduces the traffic congestions in crowded areas. Additionally, the existence of SPARTAN Superway provides flexibility to those constrained by being a 24/7 public transit system, which eventually helps to connect people to places they care about without having to be afraid to miss the last operating schedules. Since the system is fully automated and run by renewable energy, it will be beneficial towards the disabled, elderly, and the poor because not only that it will not cost much to travel, passengers can be dropped off or picked up at any convenience stations. All in all, the concept of SPARTAN Superway can improve the quality of life for individuals, as well as the environments.

7.4 Brief Synopsis of SPARTAN Superway Over the Last Seven Years

SPARTAN Superway was first developed in 2012 by Professor Burford J. Furman and Ron Swenson at San Jose State University as a senior project for graduating mechanical engineering students. However, it does not only serve as a senior project but also as a concept idea of ATN that may be integrated within the city of San Jose and hopefully, globally. Ever since, the project has three major teams, the Small Scale, Half Scale, and Full-Scale team. Each team serves different purposes in SPARTAN Superway. For instance, the Small-Scale team exists to provide better insight for the community to represent the Half, and Full Scale since the concept of SPARTAN Superway is much easier to be developed through Small Scale. Half and Full-Scale team exist to demonstrate a working and efficient prototype for the community. Hence, each team plays an essential role in SPARTAN Superway. Since there are many tasks to do, each team then is subdivided into multiple sub-teams to focus on specific tasks, such as the Bogie Integration team, Controls team, Wayside team, Drivetrain team, Guideway team, and Steering and Emergency Braking team.

There has been significant progress to the current SPARTAN Superway since the first year of development. During 2012-2013, these sub-teams worked together to develop design specifications of the SPARTAN Superway and made a Small-Scale version of it. The 2013-2014 team was able to develop the Full-Scale team, while the Small-Scale team made further improvements to their original designs. During the year of 2014-2015, the SPARTAN Superway sub-teams were able to develop and made a working prototype for demonstration. After having the prototype done, the future SPARTAN Superway team, class of 2015-2016, made a Half-Scale version of demonstrating the prototype in a cheaper option. 2016-2017 SPARTAN Superway team made further improvements to the design specifications and was able to demonstrate the pod cars moving or accelerating through curved sections. The 2017-2018 SPARTAN Superway team built an entirely new Full-Scale bogie and guideway made of wood, as well as continued work on the existing Half Scale and Small-Scale models.

8.0 Background and Context

The SPARTAN Superway project in the 2018-2019 academic year was a fresh start for the Full-Scale model. All previous designs were scrapped or repurposed in favor of building something entirely new such as a new bogie, wayside system, guideway, etc. The previous bogie system became a slave bogie that is used solely for carrying the weight of the payload. Because of this, it was an opportune time for the drivetrain system and the motors to be updated. Ron Swenson and Dr. Furman created this drivetrain team and connected the team with an outside company called Sapphire Motors, with the hope that they will help the drivetrain team in sizing and manufacturing hub motors with a high-power density, and low rpm and high torque. Unfortunately, this plan fell through roughly six weeks into the first semester, and we were looking for alternatives. Ron and Dr. Furman set out a basic set of specifications for us to follow, and we went searching for hub motors to buy, designing wheels to fit these motors, and looking at mounting the system to the Bogie designed by the Bogie Integration team.

9.0 Description of Sub-team and Objectives

For the Full-Scale 2018-2019 senior project, the drivetrain team's objective overall was to research, source, retrofit, and implement a high-power density hub motor to drive the SPARTAN Superway Full-Scale prototype. The motors are the brawn of SPARTAN Superway Full-Scale bogie because the motor acts as the wheel of the system. Without the motor, there will be no drivetrain to drive the bogies. Hence, the drivetrain team has been working closely with the wayside and bogie integration teams to ensure that the selected motor will have enough power to drive the bogie and proper clearance and mounting points to integrate with the Full-Scale bogie.

Since sourcing a compatible motor is crucial to drive the SPARTAN Superway Full-Scale prototype, the team did several motor sizing calculations to make sure that any sourced motor will have enough power to drive the bogie. The motor that the team ended up going with was a customized geared hub motor from XOFO that is capable to produce low rpm with high torque.

After sourcing a compatible motor, the team also had to design a way to allow the motor to act as a wheel and a way to mount the motor to the bogie so that the selected motor can be implemented into the system. In the end, the drivetrain team decided to go with the simplest options; around casing that fits over the existing motor so the team would not have to take anything apart. Additionally, a shaft that the motors can screw into was also designed to help mounting the motor onto the drive bogie.

The drivetrain team was also responsible for sourcing a compatible motor controller for Controls Team to control the speed at which the motor operates by Pulse Width Modulation. The controller the team ended up going with was a KBS48051X Mini BLDC controller from Kelly Controls that has a rated current of 25 amps.

The end goal the team had in mind was creating a system to be demonstrated at the 2019 Maker's Faire, so the deadline that ended up being used for the team's Gantt Chart was Wednesday, May 15, 2019.

10.0 Design Requirements and Specifications

The design requirements and specifications for the drivetrain team were drawn and set by various other Full-Scale SPARTAN Superway teams such as bogie interaction, control team, and wayside team. Along with the other team specifications, the expected deliveries for the year-end demonstration of Spartan Superway also dictated on the design criteria for the drivetrain team. The design requirements and specifications for the three engineering components of the drivetrain team are as follows:

Motors

- Brushless Direct Current Out runner hub motor
- Less than 10 inches in diameter
- Accelerate bogie system to 2 mph
- Coast bogie with a full load at a constant speed of 2 mph
- Decelerate bogie to complete stop
- Rated Power: ~600 W to ~1000 W
- Rated Voltage: 24 V to 48 V
- Speed Range: 60 RPM to 120 RPM
- Lightweight: <= 15 lbs
- Select compatible electronics and accessories such as contactors, controllers, wiring harnesses, etc.

Hub’s Wheels

- 10 inches in diameter
- Modular design that can be mount on and off the hub motors using threaded bolts
- Structurally able to support the weight of drive bogie (~600 lbs)
- Transfer torque to linear motion

Drive Bogie’s Motor Shaft

- Thread onto the existing motor shaft
- Distribute and support the drive bogie (~600 lbs)
- Resist stall motor torque of 110 N-m at each end caused by friction between the wheels and the guideway

11.0 State-of-the-Art/Literature Review for the Sub-team’s Sphere of Work

11.1 Automated Transit Network

According to Ellis, Fabian, Muller, Swenson and Dr. Furman (2014) on “Automated Transit Networks,” the concept of ATN is to provide a fully automated transport system that provides non-stop transportation services from origin to destination over a specific area of space. However, unlike any other transportation services, ATNs offer a service that brings passengers from the original point to the desired destinations without having to stop at intermediate stops. Other than that, passengers also have the freedom to travel either alone, or with companions. This service can be referred to as personal rapid transport or shorten as PRT.

In general, all ATNs falls under the bigger scheme of an automated guideway transit (AGT), in which the system operates autonomously. Although ATNs is relatively a newly developed concept, it is no longer an unfamiliar phrase for the community as there have been several implementations of ATNs over the years with numerous designs. However, not all transportation services can be considered as ATN. According to Advanced Transit Association, or shorten as ATRA, as of 2003, seven key features that must be met to earn the classify a transport system serving as an ATN. The seven key features are as follows:

1. Direct origin-to-destination service with no need to transfer or stop at intermediate stations
2. Small vehicles available for the exclusive use of an individual or small group traveling together by choice
3. Service available on demand by the user rather than on fixed schedules
4. Fully automated service (no human drivers) that can be available for use 24 hours a day, seven days a week
5. Vehicles captive to a guideway that is reserved for exclusive use
6. Small (narrow and light relative to LRT and BRT) guideways usually elevated but also at or near ground level or underground
7. Vehicles able to use all guideways and stations on a fully connected network

Currently, there are only five operational ATN systems in the world that meet all ATRA's qualification criteria -- Morgantown PRT, Park shuttle Rivium, Masdar City PRT, Heathrow shuttle, and Nature Park Shuttle. Besides the five-current operational ATN systems, there are several more in the planning stage, one of which is the SPARTAN Superway -- San Jose State University's most recent work involving the Automated Transit Network.

The Morgantown Personal Rapid Transit at West Virginia University was the first transport system that qualifies as ATN. It began its operation in 1975 that transports as many as 15,000 riders per day. The Morgantown PRT consists of 71 fleets in total that can operate on 8.7 miles of dedicated guideways with a maximum travel speed of 30 mph. Each fleet can accommodate eight passenger seats and can carry up to 20 passengers in total.
While the Morgantown PRT was the first transport system, the most modern transport system that qualifies as ATN is the ULTra PRT, which has been operating in Heathrow Airport, UK, since 2011. ULTra PRT consists of 21 vehicles that can operate on 2.4 miles route connecting the airport terminal 5 to business passengers car park. ULTra PRT can travel up to 25 mph while carrying four passengers per vehicle. After operating for two years, the system has passed the 600,000th passenger milestone.

Now that the awareness of ATN systems has increased in the community, San Jose State University introduced a similar concept of automated transportation service for the community but powered using renewable energy. The ongoing project, SPARTAN Superway that has been in development since 2012, is aiming to become a transport system that is efficient and low cost, which eventually would be fully integrated into Silicon Valley. Such objectives are achievable because SPARTAN Superway relies on solar power to operate and can operate autonomously. SPARTAN Superway consists of several sub-teams, ranging from those in charge of the integration of the bogie, braking system, and guideways to those in charge of power, controls, and motors. All in all, SPARTAN Superway hopes to be an optimized system for the community.

11.2 High Power Density Motor

As for the drivetrain team, there was no past work done regarding the motor from previous years' work, making the current 2018 - 2019 drivetrain team to be the first team in the development process. The drivetrain team was established to implement a high-power density motor that can provide enough power to drive the bogie system. Initially, the team worked closely with Sapphire Motors to build a compatible motor for the SPARTAN Superway. However, due to industry sponsor issues that the team faced, Sapphire Motors and the team was no longer in contact. Hence, a backup plan was executed.

The team found a vendor from China, XOFO motor, that could provide a compatible brushless DC (BLDC) hub motor that meets the requirements set out by Dr. Furman and Ron Swenson. The motor has specifications of rated power in the range of 600 W to 1000 W, a rated voltage in the range of 24V to 48V, and enough stall torque for speed ranging from 60 RPM to 120 RPM. Typically, hub motors are used for applications that meant to go for very long distances, with long propulsion and coasting times, such as e-bikes. However, in the case of SPARTAN Superway, where the bogie only needs to travel a very short distance of 31 feet, and with a minimal propulsion time, many hub motors on the market were not compatible.

The concept of a hub motor is an electric motor that is incorporated into the hub of the wheel. Aside from hub motors being easy to implement, it can also provide high torques for different RPMs values ranging from low to high, due to the presence of planetary gearbox. In the case of SPARTAN Superway, a BLDC hub motor would be an appropriate selection in which the mechanical commutation is replaced with electronic commutations. With that said, BLDC helps to remove all contacts between the rotor and stator and hence gives longer life for the motor. There are currently many literature and research conducted within the realm of electric automobiles. According to Sun, Li, and Liao (2017) on their analysis of wheel hub motors application on electric vehicles, they found several critical advantages of hub motors implementation such as compact structure, high utilization ratio of interior vehicle space, lower center of vehicle gravity, excellent driving stability, easy intelligent control, and many other advantages including maintenance costs. These advantages of hub motors are something that SPARTAN Superway is looking forward to having in order to improve its drive train design. Although, it was mentioned in the analysis that wheel hub motors carry the disadvantage of increasing spring mass in electric vehicles, the issue might not be too relevant for a transportation system on a guide way that is smooth and flat.

12.0 Design Description

12.1 Hub Motor and Wheel Design

The design of our team's wheels for the drive bogie was dependent on the hub motor that we would be sourcing. With our initial requirements of having the drive bogie wheel sized to be 10 inches in diameter meant that our hub motor would have to be smaller than 10 inches while matching all the criteria listed in section 10. After talking to several manufacturers and vendors, we ended up going with XOFO's SOFN hub motor. The first step in designing our wheels for the system was to create a 3D model of our motor in SolidWorks to use as a reference. This was achieved by taking measurements of the motor, along with the provided drawing by XOFO, which contains a few of the overall SOFN motor dimensions, as shown in Figure 3. The recreated 3d model of XOFO's SOFN hub motor can also be seen below in Figure 4. Although some of the features of the 3D cad motor were true to the model, it still sufficiently as a reference to design the wheels.

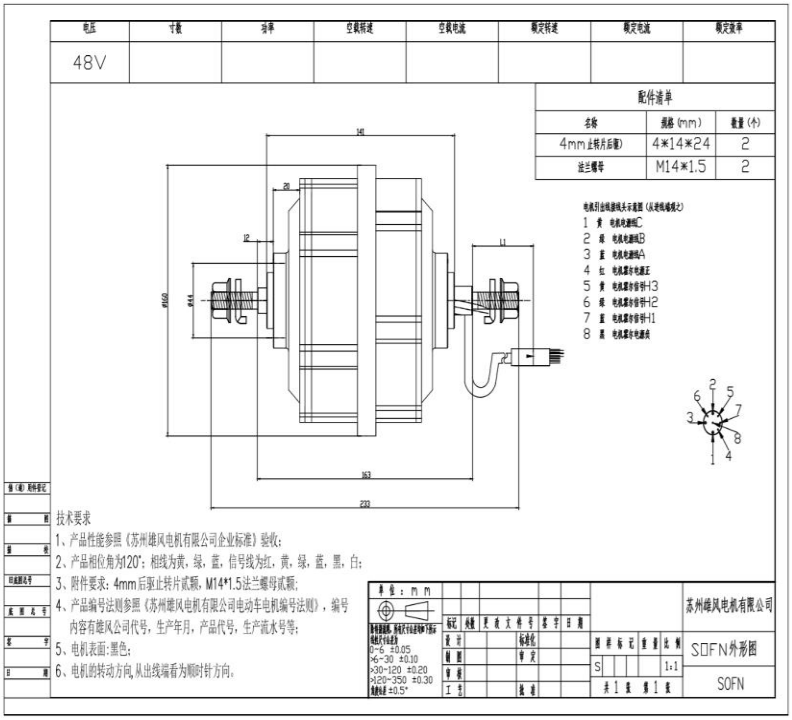

Figure 3: Drawing of SOFN Hub Motor Provided by XOFO

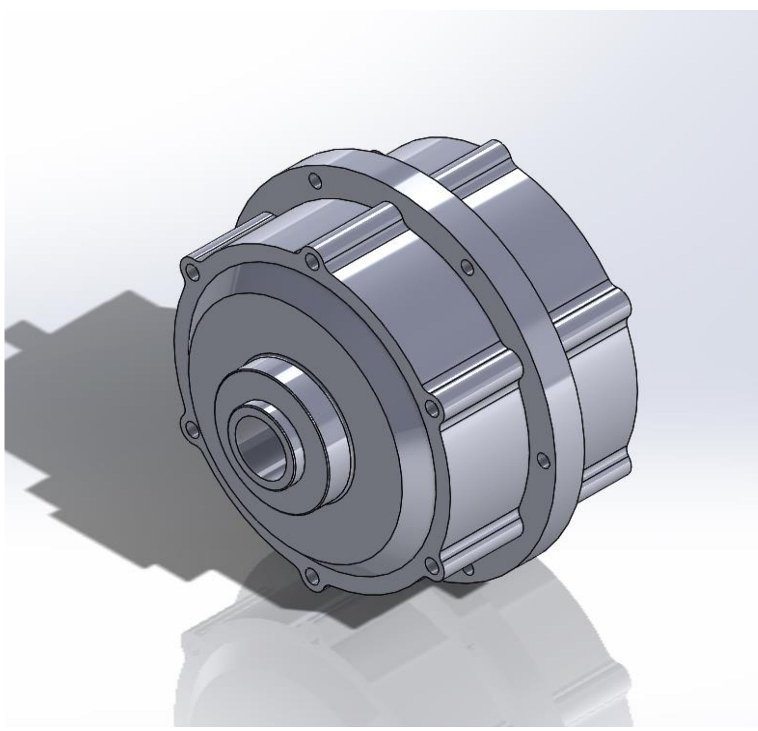

Figure 4: The Recreated 3D CAD Model of the SOFN Hub Motor

The original design that the team had for the hub motor wheel was a rim where a pneumatic tire would be able to be mounted on, as shown below in Figure 5. The design would consist of two rim halves where each half would be fitted snugly onto the motor and be secured with six threaded bolts. Although the design for this rim/wheel was ideal, the manufacturing costs and time to machine this design would be costly and expensive. To reduce costs and manufacturing time, we decided to go with a much simpler design where a pneumatic tire is not needed, and the two halves would form into a cylindrical wheel itself. The cad model of our final wheel design can be seen below in Figure 6, and the exploded view can be seen in Figure 7. This wheel halves are made from 6061-T6511 aluminum due to the light weight and high strength characteristics of tempered 6061. The main benefits of this new design besides manufacturing costs are the reduction in rolling resistance due to the nature of aluminum as opposed to having rubber tires, along with lower maintenance cost as rubber tires can wear down quickly.

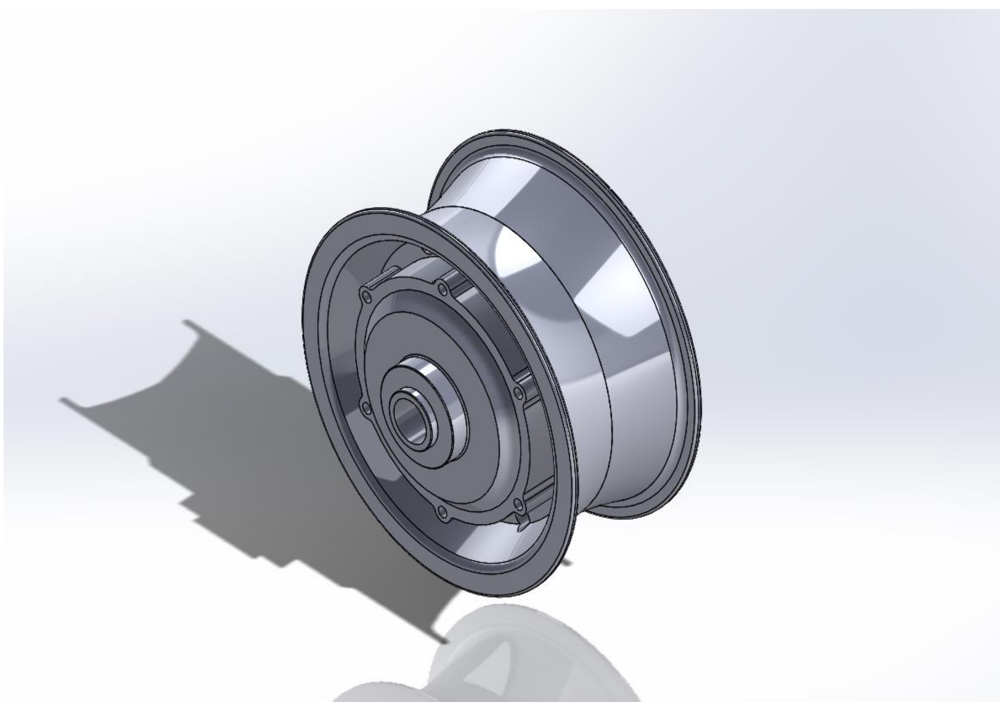

Figure 5: 3D CAD Design of Original Idea of Motor Casing Acting as Rim

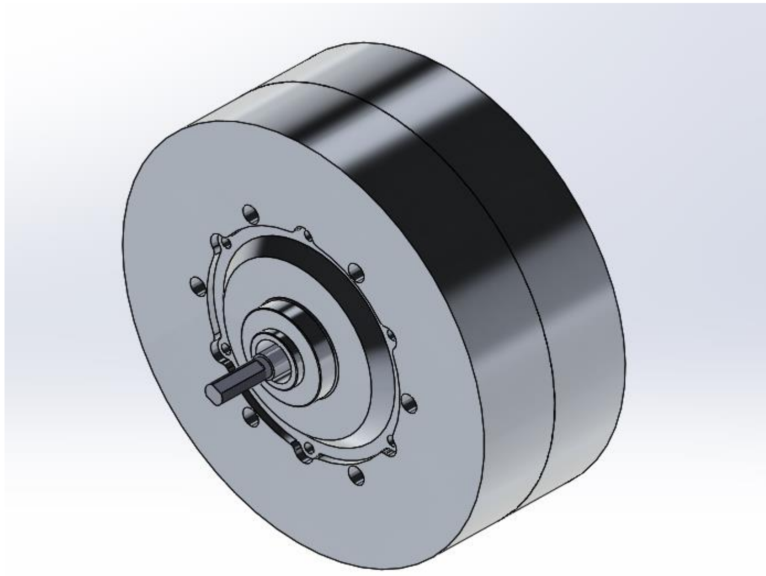

Figure 6: Final 3D CAD Design of Motor Casing Acting as Wheel

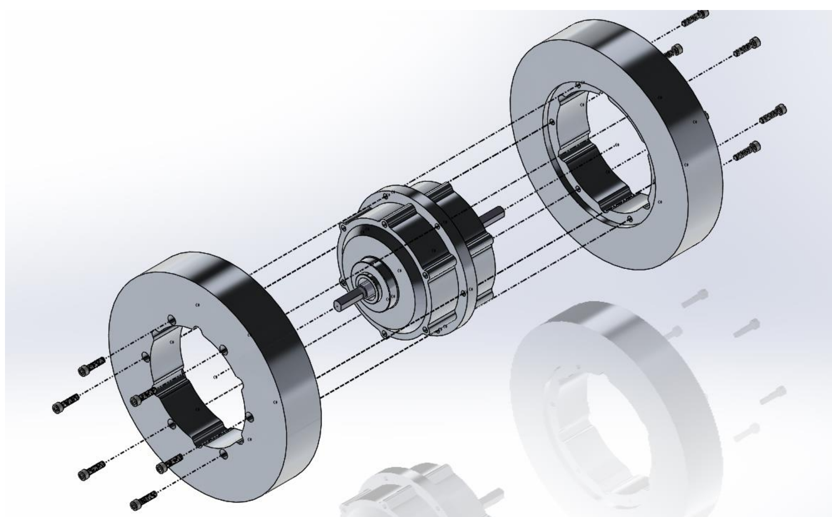

Figure 7: Exploded View of Motor Casing with the Motor

12.2 Axle Design

The axle is an integral component to the integration of the motor to the bogie. While working with the bogie integration team to discuss mounting options, it was decided that the easiest way to mount the motors to the bogie would be a single axle, threaded to the motor shaft. The axle was machined in the SJSU machine shop and was made with 2024 Aluminum. The reason for this was weight distribution, as we wanted most of the system's weight to be on the wheels. We chose 2024 because it is a sturdy alloy and was supposed to take threads well.

However, we realized that the 2024 aluminum was a wrong choice, as we are experiencing stripping when we take the motors out. We had to get the shaft machined twice, as the threads in the axle did not match the threads on the motor. The original assumption was that the axle would be completely stationary once fitted in, due to tight tolerancing and the fact that the motors are out runner motors. This means that the axle within the motors does not spin. However, the holes in the bogie had to be widened due to the holes not lining up.

Furthermore, we realized there is some torque acting on the motor due to friction between the motor and the ground, that will cause the motor to unthread from the screw. To counteract both these things, we decided to place two face mounted shaft collars on the axle, that mounts onto the bogie's walls. The CAD drawing of the axle can be seen below in Figure 8, and a picture of the axle with the collars is below in Figure 9.

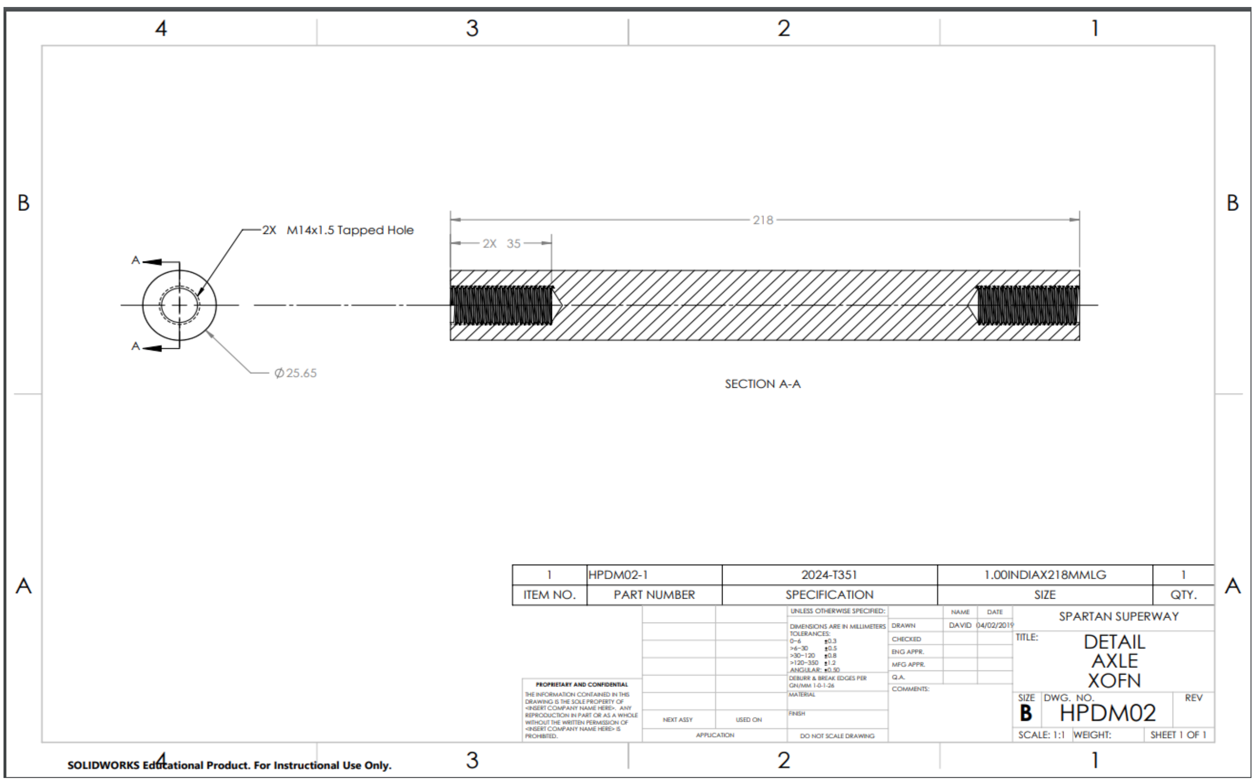

Figure 8: CAD Drawings of Axle

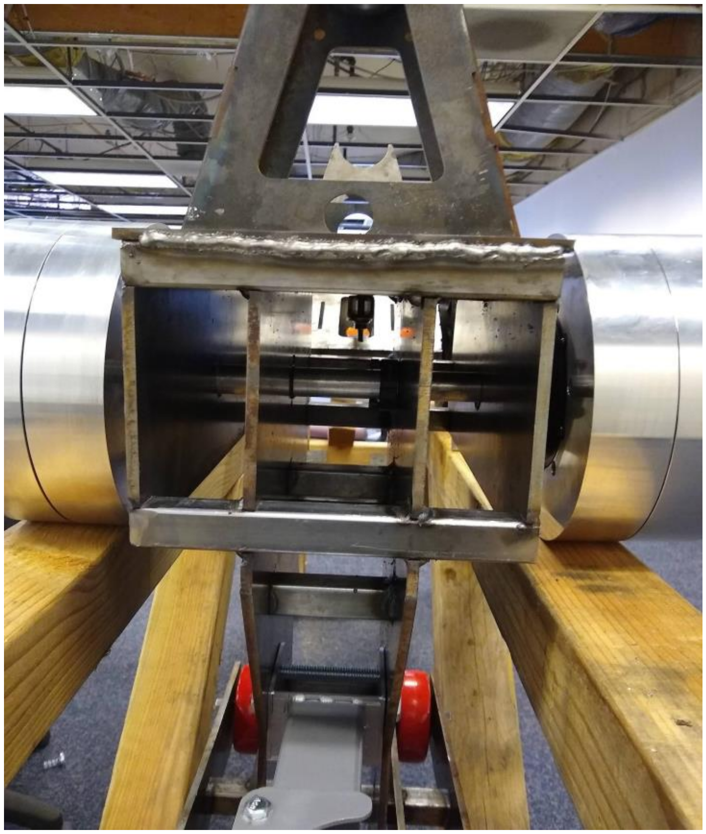

Figure 9: Location of Axle and Collars in the Drive Bogie

12.3 Wiring Bracket Design

The wiring bracket was a component that the team realized was needed after finding out from the control team that the motor can only be operated at half of the forward speed in the reverse direction. This means that to have the two motors on the drive bogie rotating at the same speed, one of the motors would have its wire sticking out away from the bogie. This can potentially lead to a situation where the wire might interfere with the rotating wheel and end up ripping the electronics out of the bogie. The wiring bracket is designed to be mounted on the motor shaft, which will remain stationary during operation, and provides a surface for the wiring to travel on that is away from the wheel. The wiring bracket was 3d printed using PLA to save manufacturing cost and time. The design for the wiring bracket can be seen below in Figure 10.

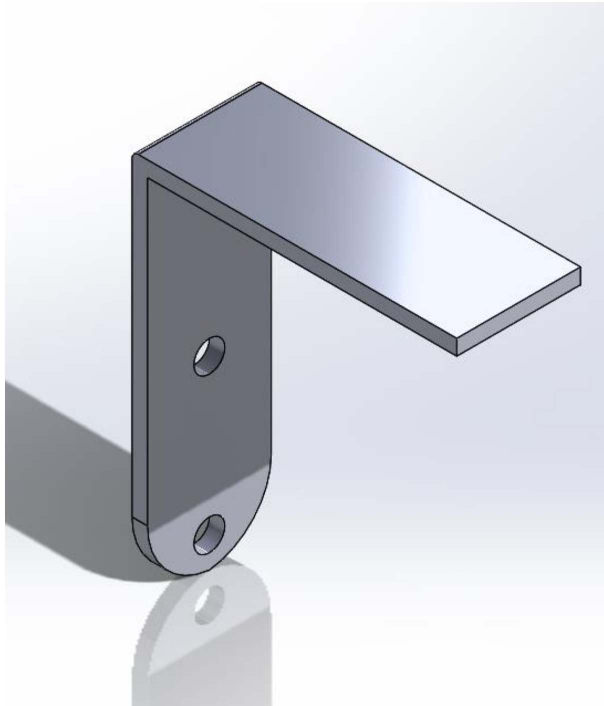

Figure 10: 3D Design Model of Wiring Bracket

13.0 Analysis/Validation/Testing

13.1 Kinematic Computation

Before making decisions on the type of motor to purchase, some analysis needs to be done beforehand -- such as kinematic computations and motor sizing. Since the motor will be running in constant acceleration, the motor experiences constant changes in velocity over an equal period. Hence, the motor's motion can be calculated through simple kinematic equations involving displacements, initial and final velocity, time, and acceleration. In this case, the four equations of motion for constant accelerations are:

$$s = V_o t + 0.5at^2 \qquad (13.1)$$

$$V_f = V_o + at \qquad (13.2)$$

$$V_f^2 = V_o^2 + 2as \qquad (13.3)$$

$$s = \frac{1}{2} (V_o + V_f) * t \qquad (13.4)$$

Where s is the displacement, Vo is the initial velocity, V_f is the final velocity, t is total time, and a is the acceleration.

Now that the equations have been settled, the drivetrain team ran two different cases with different numbers into the equations above. For the first case, the team assumes that the acceleration and deceleration to be 2 seconds each. With a requirement of the bogie to be coasting for 2 miles per hour, or 0.895 m/s, the acceleration of the bogie can be calculated through Equation (A-2), and the kinematic visualization can be seen in Figure 11:

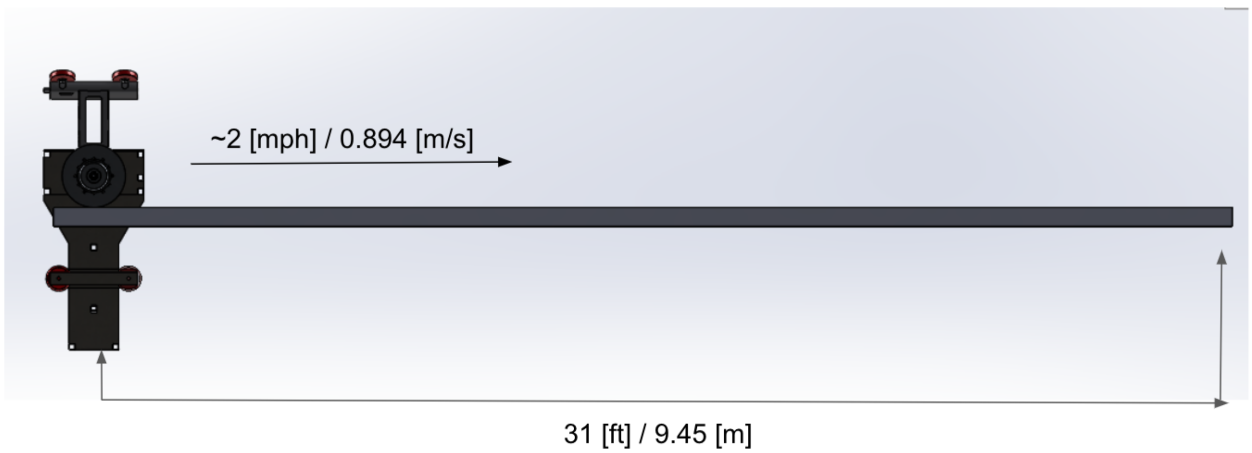

Figure 11: Kinematic Visualization of the Initial Parameters

$$0.895\,[m/s] = 0\,[m/s] + a\,[m/s^2] * 2\,[s]$$
$$a = 0.4475\,[m/s^2]$$

Using Equation (A-4), displacement can be calculated by:

$$s = ½ * (0\,[m/s] + 0.895\,[m/s]) * 2\,[s] = 0.895\,[m]$$

The team then measured the total track of the length, which turned out to be approximately 9.45 m long. Subtracting the total distance with the displacement of acceleration and deceleration:

$$d = 9.45\,[m] - 0.895\,[m] - 0.895\,[m] = 7.66\,[m]$$

The distance left for coasting was calculated to be approximately 7.66 m long. Then, using Equation (A-4), the coasting time was found to be:

$$7.66 \text{ [m]} = \frac{1}{2} * (0.895 \text{ [m/s]} + 0.895 \text{ [m/s]}) * t \text{ [s]}$$

$$t = 8.56 \text{ [s] of coasting.}$$

For the second scenario, the team assumes that the acceleration and deceleration to be 1 second each. With a similar requirement as the first case, the bogie needs to coast for 0.895 m/s. Hence, using Equation (A-2) will yield a value of for acceleration to be:

$$0.895 \text{ [m/s]} = 0 \text{ [m/s]} + 1 \text{ [s]} * a \text{ [m/s}^2\text{]}$$

$$a = 0.895 \text{ [m/s}^2\text{]}$$

Using Equation (A-1), the displacement can be calculated by:

$$s = 0 \text{ [m/s]} * 1 \text{ [s]} + \frac{1}{2} (0.895) \text{ [m/s}^2\text{]} * (1)^2 \text{ [s]}$$

$$s = 0.4475 \text{ [m]}$$

Subtracting the total distance with the displacement of acceleration and deceleration:

$$d = 9.45 \text{ [m]} - 0.4475 \text{ [m]} - 0.4475 \text{ [m]} = 8.55 \text{ [m]}$$

The distance left for coasting was calculated to be approximately 8.55 m long. Then, using Equation (A-4), the coasting was found to be:

$$8.55\text{[m]} = \frac{1}{2} * (0.895 \text{ [m/s]} + 0.895 \text{ [m/s]}) * t \text{ [s]}$$

$$t = 8.54 \text{ seconds of coasting.}$$

After performing several kinematic simulations, the final kinematic visualization can be seen on Figure 12.

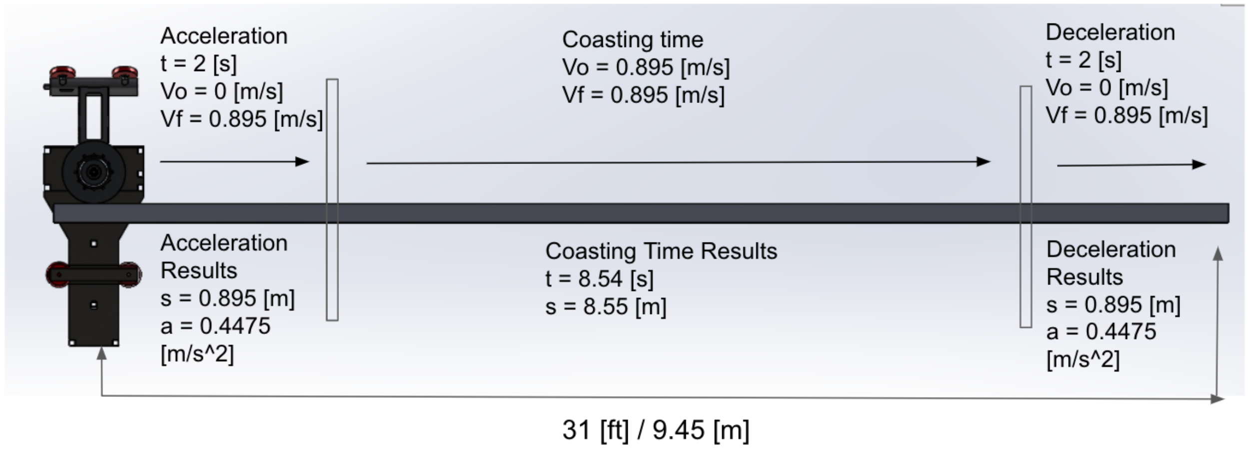

Figure 12: Kinematic Visualization for the Final Simulation

13.2 Motor Sizing

In order to source the proper motor for the project, proper motor sizing needed to be conducted. Proper motor sizing requires several important parameters and operating conditions to be identified. These parameters include the weight, wheel diameter, wheel weight, number of wheels, and rolling coefficient between wheel and floor for both the drive bogie and slave bogie; while the operating conditions consist of operating speed and acceleration time. These parameters, operating conditions, and their values can be seen below in Table 1. It is important to note that these parameters were mostly estimated since sizing and sourcing was something that was done in the early stages of the project, and the values were still unknown; however, to compensate for the lack of certainty, we made sure to account for the worst case scenario. An example of accounting for the worst-case scenario would be using a rolling coefficient of 0.01 for a tire on concrete instead of just taking the rolling coefficient of steel on steel, along with a low system efficiency of 65%.

Table 1: Parameters of Overall System

Parameter	Symbol	Value	Units
Drive Bogie			
Vehicle Weight	W_1	551.6	lbs
Wheel Outer Diameter	D_1	10	inch
Wheel Weight	W_{D1}	30	lbs/pc
Number of Wheels	n_1	2	pc
Rolling Coefficient Between Wheel and Floor	μ_1	0.01	
Slave Bogie			
Vehicle Weight	W_2	350	lbs
Wheel Outer Diameter	D_2	10	inch
Wheel Weight	W_{D2}	10	lbs/pc
Number of Wheels	n_2	4	pc
Rolling Coefficient Between Wheel and Floor	μ_2	0.01	
System Efficiency			
Drive Mechanism Eff.		65 %	
Operating Conditions			
Operating Speed	V_1	176	ft/min
Acceleration Time	t_1	2	s

Once the parameters and operating conditions were identified, the torque and speed requirements are then able to be sized. To properly size the required torque for the motor, the first step is to calculate the total load inertial using equation (13.2.3) by taking the sum of drive bogie's load inertia and the slave bogie's load inertia, which can be calculated using equation (13.2.1) and equation (13.2.2) respectively. With the attained load inertia, the acceleration torque can be calculated using equation (13.2.4).

$$J_{drive} = (W_1 + (1/2)\, W_{D1} \times n_1) \times 16 \times (D_1 / 2)^2 \qquad (13.2.1)$$

$$J_{slave} = (W_2 + (1/2)\, W_{D2} \times n_2) \times 16 \times (D_1 / 2)^2 \qquad (13.2.3)$$

$$\text{Total Load Inertia: } J_L = J_{drive} + J_{slave} \qquad (13.2.3)$$

$$\text{Acceleration Torque: } T_a = (J_L / 386)\, (V_m / (9.55 \times t_1))\, (1 / 16) \qquad (13.2.4)$$

With the Acceleration torque calculated for the second torque that is needed is the loading torque. In solving for the loading torque, the net force acting on the system is needed. Equation (13.2.5) below can be used to calculate the force acting on the system, which most of the purely rolling resistance since drag is neglected for low-speed operation. Loading torque can be acquired using the calculated force value through equation (13.2.6). Once both acceleration torque and loading torque is found, equation (13.2.7) is used to find the required torque sizing that the motor needs. The torque sizing is published below in Table 2, where the required torque is calculated with a safety factor of 1.5.

$$F = (W_1 + n_1 \times W_{D1}) \times (\sin\alpha + \mu_1 \cos\alpha) + (W_2 + n_2 \times W_{D2}) \times N \times (\sin\alpha + \mu_2 \cos\alpha) \qquad (13.2.5)$$

$$\text{Loading Torque: } T_L = (F \times D_1) / (2\, \eta \times 0.01) \qquad (13.2.6)$$

$$\text{Required Torque } T = (T_a + T_L)\, (\text{Safety Factor}) \qquad (13.2.7)$$

Table 2: Torque and Speed Calculation Results

Parameters	Results
Total Load Inertia (kg-m^2)	3.48
Required Torque per Motor (N-m)	24.92
Loading Torque per Motor (N-m)	4.35
Acceleration Torque per Motor (N-m)	12.26
Operation Speed (rpm)	67.26

13.3 Motor and Controller Selection

After calculating and sizing the required specifications needed to drive the SPARTAN Superway for Makers Faire, the next step was to source an appropriate motor that would fit the specifications. The motor that best matches the objectives was XOFO's SOFN brushless DC hub motor. This is a customized motor from XOFO for their previous client who requested a high torque and low-speed motor. The specifications of this motor, as reported from their sales representative can be seen below in Appendix Table 7, while the overall dimensions of this motor can be seen in Figure 3. With the provided motor specifications, the drivetrain team ran several theoretical testing to make sure that the hub motor can drive the SPARTAN Superway during the Makers Faire. For the first case, the team wanted to make sure if the motor has enough power to move the SPARTAN Superway. Hence, the team calculated the power input, power output, and transmission efficiency using the following equations:

$$P_{in} = V * I \qquad (13.3.1)$$

$$P_{out} = \tau * \omega \qquad (13.3.2)$$

$$Transmission\ efficiency = 100 * [P_{out} / P_{in}] \qquad (13.3.3)$$

Using the equation (13.3.1) and the parameters of 13 A current and 48 V rated voltage,

$$P_{in} = 48\,[V] * 13\,[A] = 624\ [\mathrm{W}]$$

Then, using the equation (13.3.2) and the parameters of 52 Nm torque and rated speed of 90 RPM,

$$\omega = 90 \frac{rev}{min} * \frac{2\pi\, rad}{rev} * \frac{1\, minute}{60\, sec} = 9.426 \frac{rad}{sec}$$

$$P_{out} = 52\, [Nm] * 9.426\, [rad/s] = 490.152\, [W]$$

With both power input and power output values obtained, substituting both values into the equation (13.3.3), the transmission efficiency was found to be

$$Transmission\ efficiency = 100 * (\frac{490.152}{624}) = 78.53\%$$

Then, listing all the known parameters and the obtained theoretical transmission efficiency result,

Table 3: Known vehicle parameters and obtained theoretical transmission efficiency

Parameters	Values
Total Mass, m [kg]	453.6
Rolling Resistance, C_r	0.01
Air Density, ρ $[kg/m^3]$	1.23
Drag Coefficient, C_d	0.47
Reference Area, A $[m^2]$	0.116
Transmission Efficiency, η [%]	78.53
Wheel diameter, D [m]	0.254

With the obtained parameters; the rolling force, drag force, and total power can be calculated using the following equations listed below. Then, the total power required for the motor to drive the SPARTAN Superway can be seen on the result Table 4 and Figure 13.

$$F_{roll} = C_r * m * g * v \quad (13.3.4)$$

$$F_{drag} = 1/2 * \rho * C_d * A * V^3 \quad (13.3.5)$$

$$P_{required} = Gear\ ratio * (F_{roll} + F_{drag})/(\eta/100) \quad (13.3.6)$$

Table 4: Power Required for the Motor to Drive SPARTAN Superway Calculation Results

V $[km/h]$	V $[m/s]$	F_{roll}[N]	F_{drag}[N]	$P_{required}$[W]
1	0.3	12	0	109
2	0.6	25	0	217
3	0.8	37	0	326
4	1.1	49	0	435
5	1.4	62	0	544

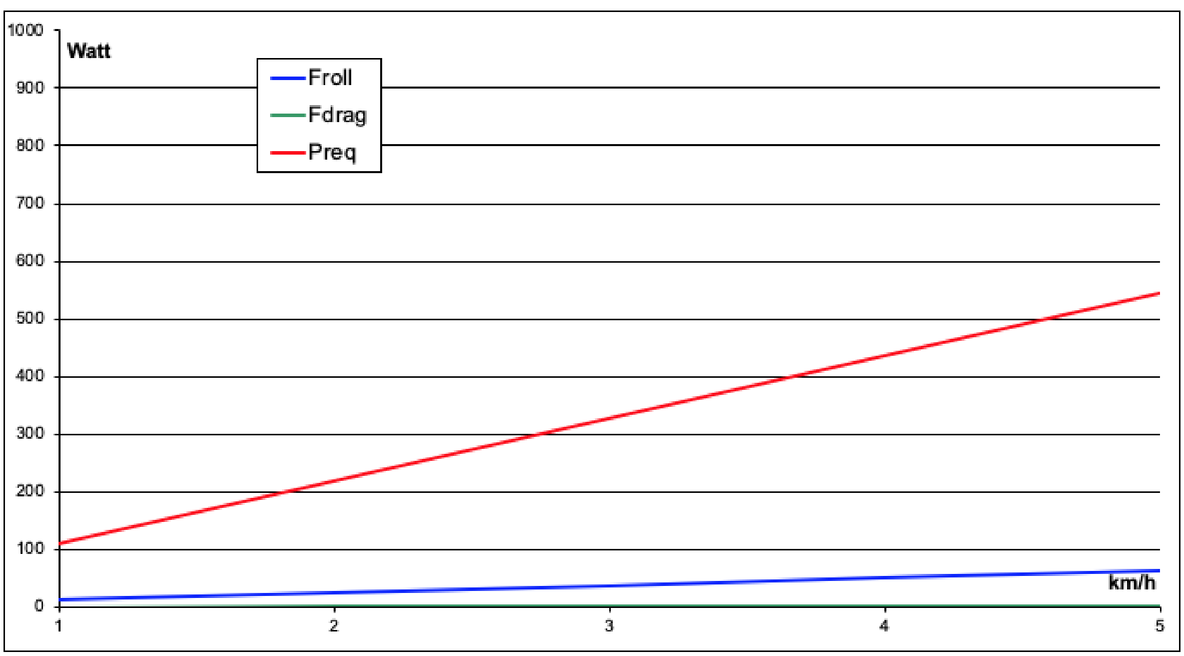

Figure 13: Graph of Power Required, Drag Force, and Rolling Force.

After comparing the motor specifications with the theoretical motor sizing, as well as the power calculations, this motor fares very well with overcoming the torque requirement of 24.92 N-m with its stall torque of 110 N-m, along with its continuous torque of 53 N-m in comparison to the loading torque requirement of 4.35 N-m.

In addition to the sourcing a motor, the drivetrain team also must pick a compatible controller to communicate with the motor. However, not all controllers can do the work because of the high rated power and current that the motor has. Since the motor has a rated power of 750 watts and a rated voltage of 48 volts, the current that the controller must withstand can be calculated by dividing the rated power with the rated voltage. With that said, the rated current was calculated to be approximately 15.625 amps. After contacting several controller vendors, the controller of choice is the KBS48051X Mini Brushless DC motor controller from Kelly Controller. According to the datasheet of the controller that can be found in Table 8 of Appendix, the controller of choice has a maximum operating voltage of 24 to 48 volts, a continuous current limit of 25 amps and a peak current limit of 50 amps for 30 seconds. With that said, the controller of choice will be compatible with the motor that the team has sourced.

13.4 Wheel Design Testing/Validation

Testing and validation for XOFO's SOFN wheel design was something that heavily involved the use of rapid prototyping. One of the main design goals for the wheel was to have it fit snugly on the motor geometry. Although there will be six bolts that are responsible for securing each half of the wheels onto the motor, the snug fit design of the wheels will help in reducing the shear stress on the bolts. From rapid prototyping, adjustments and revisions to the design were able to be made in an efficient manner that resulted in the desired dimensions for the wheel. Revisions and final dimensions for the wheel can be seen in Figure 14 below.

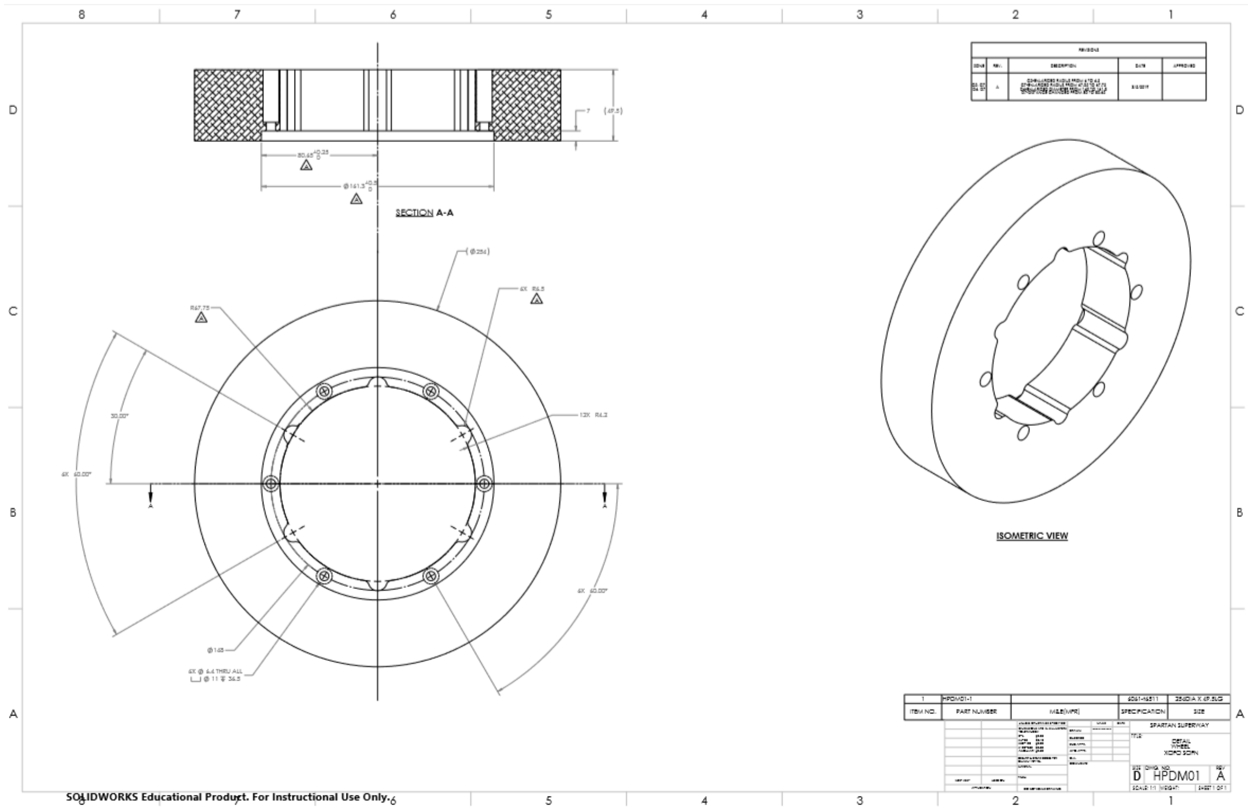

Figure 14: Final Revisions of the Motor Casing

The wheel design was also subjected to a stress analysis using a Hertzian Contact Stress analysis tool that was provided by Amesweb. The original plan was to conduct an FEA analysis using SolidWorks. However, due to difficulty in limitation of processing a non-linear analysis of a line contact between the wheel and guide rail surface, the Hertzian Contact Stress analysis module would give a much better approximation than a linear FEA analysis. The criteria used for the analysis setup, along with the stress results, can be found in Table 5. The plot for the result of shear stress versus depth can be found in Figure 15. The material that was chosen for the guideway surface was assumed since the Guideway team has yet to decide on the material that will be used. Also, it is essential to note that the Force [F] of 1539 lbf is approximated by assuming that each wheel on the drive bogie will be supporting half the weight of the drive bogie, along with the wheel weight itself. This equates to a total of 307.8 lbf per wheel and factor in with a safety factor of 5 times to account for any weight transfer and dynamic forces results in the 1539 lbf that is used for the analysis. Comparing the results of the analysis with the properties of 6061-T6511, whose ultimate tensile strength is 45000 psi and shear strength is 3000 psi, the 6061-T6511 will fare up exceptionally well to the stress.

Table 5: Hertzian Contact Stress Analysis Input Parameters and Results

Input Parameters			
Parameters	**Wheel 6061-T6511**	**Guide Way (4041)**	**Unit**
Object Shape	Cylinder	Plane	
Poisson's Ratio [v_1, v_2]	0.33	0.29	
Elastic Modulus [E_1, E_2]	10000	29700	ksi
Diameter [d_1, d_2]	10		inch
Force [F]	1539		lbf
Line Contact Length [l]	99		mm
Results			
Maximum Hertzian Contact Pressure [$_{max}$]	14476.4		psi
Max Shear Stress [$_{max}$]	4347	4347	
Depth of max shear stress [z]	0.014	0.014	inch
Rectangular contact area width [2b]	0.035		

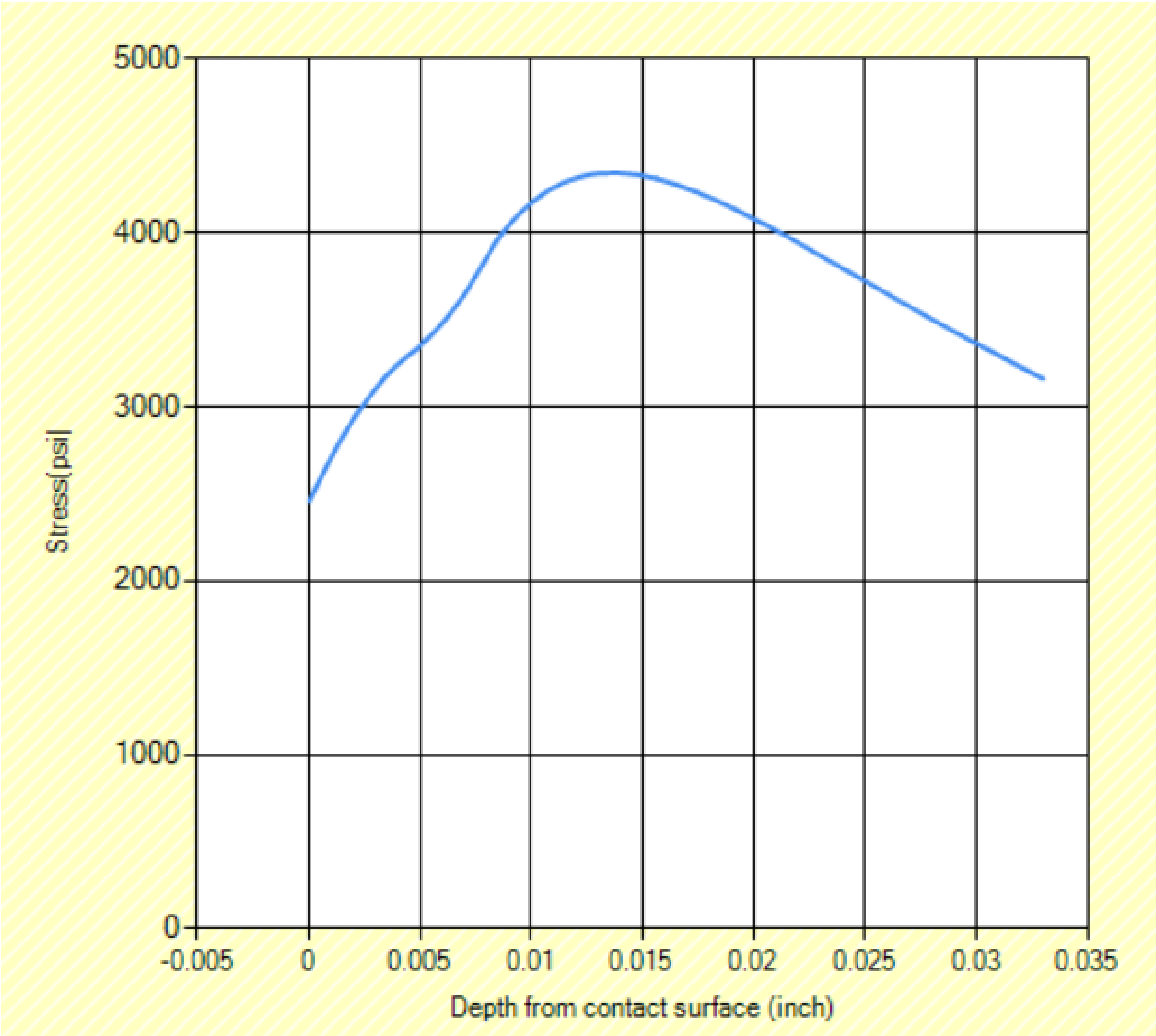

Figure 15: The Plot for the Result of Shear Stress Versus Depth

13.5 Axle Design Testing/Validation

The axle is an integral component in supporting the weight of the drive bogie and securing the motors, went through extensive FEA analysis and bench testing. In conducting the FEA test, two stress scenarios were taken. The first being a static structural bearing load. The bearing load is used to simulate the four holes on the four walls of the drive bogie that the axle is fitted into and uses to support the drive bogie. The FEA results for the axle under bearing load can be seen in Figure 16 below. The factor of safety that is derived from the stress analysis and using the yield strength of 2024-T4 is approximately 19. This shows that the design will sufficiently handle the bogie's load reliably.

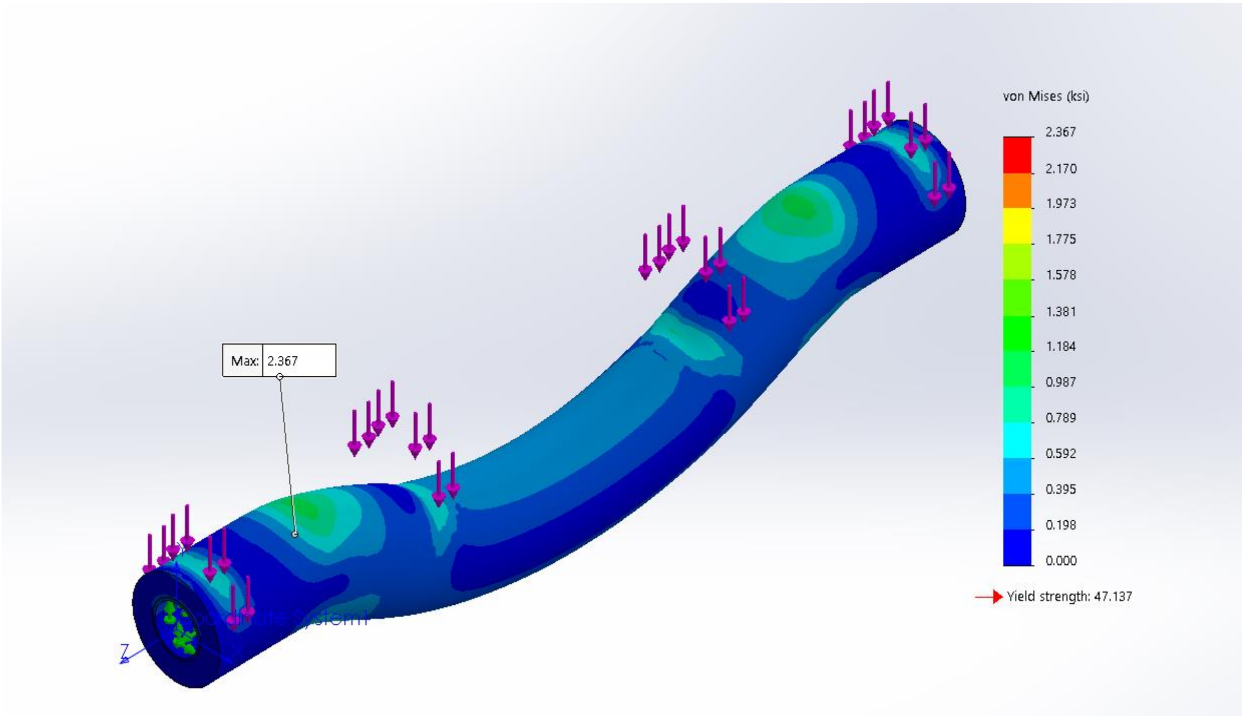

Figure 16: The FEA Results of the Axle Under Bearing Load

The second FEA test that was conducted was the reactive motor torque that is transferred from the motor shaft to the axle. To simulate the motor torque, the stall torque, 110 N-m, was applied at each end of the axle resulting in a safety factor of 3.8 and a max von Mises stress of 86.470 MPA as shown in Figure 17. With a 3.8 factor of safety, the axle design can be considered safe to implement; however, for additional stress relief on the axle and securement of the axle, face mounted lock collars were also implemented. There would be two face mounted lock collars that would each be mounted with two ¼ inches black oxide alloy steel bolt. The face mount lock collars and its location can be seen in Figure 18. To verify the effectiveness of the mounting collars, the maximum allowable torque of the ¼ inch black oxide alloy steel bolt of the collars when mounted on the axle was calculated for by using equation 13.5.1 below. The calculated allowable torque for the bolts came out to be 746 N-m which equates to a safety factor of 6.8 about the 110 N-m stall torque that is produced by the motor.

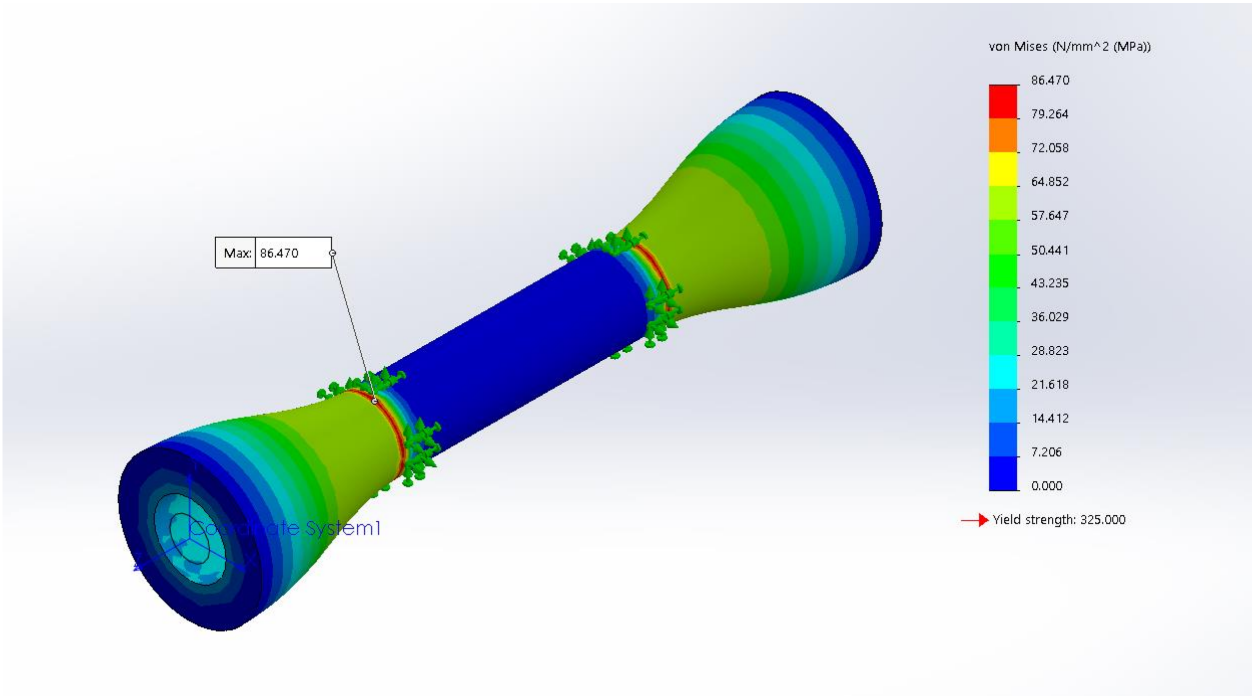

Figure 17: The FEA Results of the Axle Under Bearing Load

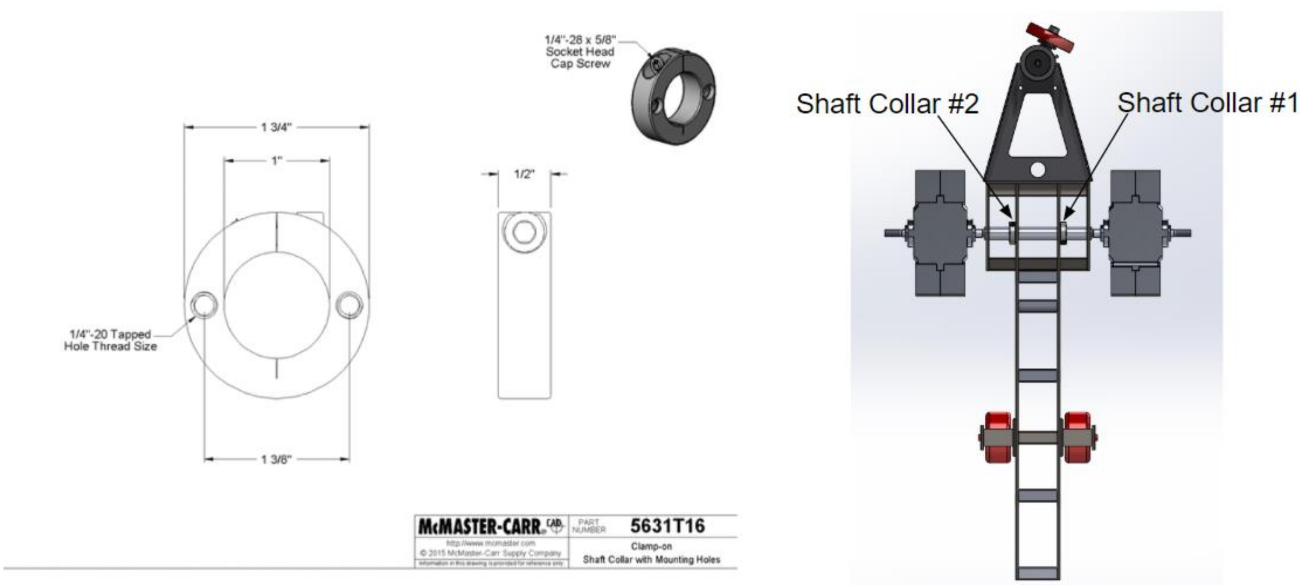

Figure 18: The Face mount Lock Collars and Its Location on the Drive Bogie

$$T_{max} = n * (\tau * A_s) * \frac{d}{2} \quad (13.5.1)$$

Where:

T_{max} is the max allowable torque (N-mm)

n is the number of bolts

τ is shear strength of black oxide alloy steel (MPa)

A_s is the cross-sectional area of the bolt (mm^2)

d is the bolt circle diameter (mm)

14.0 Bill of Materials

Most of the budget for drivetrain team was spent on sourcing a compatible high-power density geared hub motor for SPARTAN Superway. It was initially planned that the SPARTAN Superway bogie was going to use four motors to move. However, in order to cut down the overall cost of the project, the team managed to size and source a compatible motor that can drive the bogie without needing four motors. Reducing the number of motors that are going to be used by half, the team bought an extra motor for testing purposes. The cost of the motor cost the most out of the others because of the rarity of the hub motor. The hub motor of choice must be customized due to the high torque high RPM requirements to operate SPARTAN Superway. Aside from motors, two sets of controllers were also bought to control the two motors that are going to be used. The remaining items that were bought were used to retrofit the motors and help to support the controllers to communicate with the motors. For instance, the aluminum rod was used for manufacturing shaft, shaft collar was used to support the system's torque, and voltage contactors were used to satisfy the voltage requirements between the power source, controller, and motor. The overall cost of the project can be seen in Table 6.

Table 6: Bill of Materials

Item	Description	Qty.	Price
Motor Controller	KBS48051X,25A,24-48V, MINI BRUSHLESS DC CONTROLLER	2	$200.00
High Power Density Motor	SOFN XOFO HUB motor 750w; 36v; 163 mm open size; 35 km/h with hall sensor; without speed sensor; 9 pins Juliet cable; 200 mm disc brake	3	$717.20
Aluminum Rod	Aluminum 2024-T351 Bare Cold Finish Round 0.75" Cut to: 10-12" random length	2	$38.10
9 pins Juliet Adaptor	Juliet to Molex Adaptor	2	$100.00
Contactors	ZJW 100A Main Contactor - Kelly Controls	2	$65.00
Face Mount Shaft Collar	Shaft Collars with Mounting Holes and ¼”-28 x ⅝” Socket Head Cap Screw	2	$28.22
Pack of Screws	Black Oxide Alloy Steel - ¼ x 1in length	1	$8.55
		Grand Total	$1,157.07

15.0 Results and Discussions

From our analysis and testing, our motors and its components should have no trouble of driving SPARTAN Superway for the demonstration set criteria. By using proper motor sizing analysis, the XOFO’s SOFN hub motor was able to provide the necessary torque to meet the goal of accelerating the system to two mph in two seconds. The wheel can integrate seamlessly with hub motors for a modular design, as well as transferring the torque to linear motion. The axle was also able to successfully secure the hub motor to the drive bogie, along with bearing the weight of the drive bogie and torque from the hub motor as per the FEA analysis has demonstrated. Along with our custom designs, we were also able to successfully sourced and sized electrical components such as controllers, voltage contactors, and cables to run the motors sufficiently. However, we did run into an issue where one of the controllers was defective, resulting in one of the motors not being able to run. The issue was brought up last minute by the control team since most of the testing were done using the first initial controller.

With the designs being functional, other sub-teams of SPARTAN Superway are then able to utilize the designs and components for their need. Some of the teams that are dependent on our success include the control team, wayside power team, and bogie interaction team. The control team would need us to provide them with the compatible controllers and electrical components for their program to run and interact with the hardware. The wayside team would need us to provide the current and power rating for the motor for them to size their power supply with the proper ultracapacitor. Finally, the bogie interaction team would need our hub motors, wheels assembly, and axle to have a fully functioning drive bogie. The work that our team does significantly affects the outcomes and goals of the other SPARTAN Superway sub-teams; therefore, it is crucial for the team to sized, sourced, and designed everything with careful considerations.

16.0 Conclusions and Suggestions for Future Work

Our team result overall is on the positive side. Although we were not able to fully demonstrate our design due to a faulty controller and the other sub-teams not being able to integrate their component, we indeed were able to achieve our task of experimenting with the implementation of hub motors onto SPARTAN Superway. We do have some suggestions on how to improve our system for other drivetrain teams in the future. One of the main weak points of the designed system right now is the axle. The threads are stripping, and the mounting is not great. One recommendation would be to replace the axle with steel. Right now, it is made of 2024 aluminum, which causes the stripping issue.

Furthermore, the addition of steel makes it weldable to the bogie, which fixes the mounting issue. We also recommend that next year's team investigate reducing the width of the wheel casing. It is not necessary to have a big, 4-inch wide wheel, and it would be a reduction in material costs and weight. Another possible issue is the motor threading off the shaft. Our suggestion to tackle this issue would be to implement a lock washer to the motor shaft. The motors shaft is not entirely round so a lock washer, as shown in Figure 19 can be used to absorb the torque and keep the motor from threading off the motor. In addition, another important system that is recommended for future work is the implementation of a braking system. Currently, the braking is conducted electronically through the built-in brake function from the controller; however, for scalability, it is highly suggested to have a type of friction brake on the system. This is extremely important to have when the system is operating at high speed or on declines, as the electronic braking performance is inferior to that of a disc brake. Besides these technical improvements, some essential suggestions in general that we have are when working on electronic components selections is always to buy surpluses to prevent the issue of faulty electronics, as well as always staying in communications with other sub-teams. It is significant to stay in communication and even work with other sub-teams frequently because when the time comes to integrate all systems, it will become much more straightforward if everyone is on the same page.

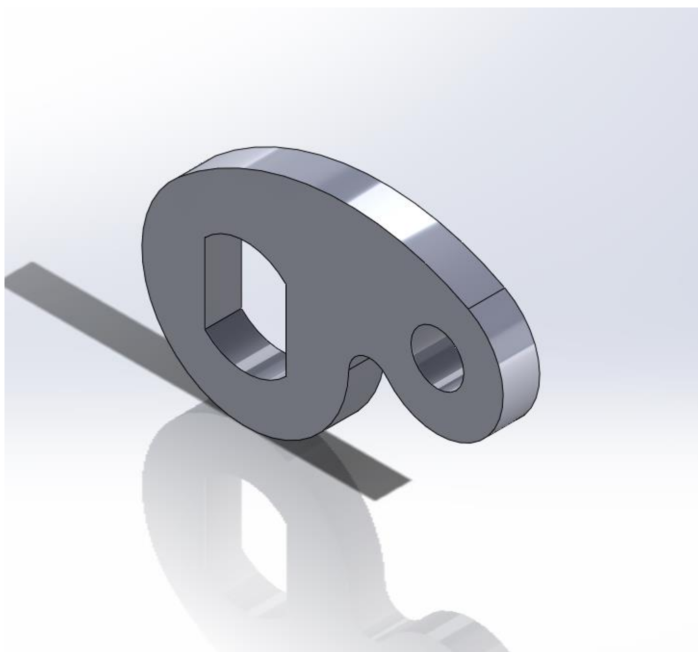

Figure 19: Lock Washer to Absorb Torque and Keep Motor from Unthreading Itself

17.0 Conclusions and Recommendations

We also have some recommendations about our project in the context of the whole Superway. The main recommendation we have would be to scrap the hub motors for the production model. While they are easier to work with as they do not require a drive system, and are a smaller form factor, all the hub motors out right now are built for electric bikes and cannot be used for any high loads. Therefore, we do not think they should be used for the production model unless the team solely focuses on research and development of a specialized hub motor for SPARTAN Superway specifically. The issue we found with hub motors is that it is quite challenging to achieve high torque and high speed. Even though torque requirements for the pod car/ bogie system are much lower than that of the conventional mass transit system, but due to the nature of SPARTAN Superway overhanging the roads and the city, there will be several steep inclines that it would need to overcome. For a hub motor to having high torque, the ideal solutions are to have a gearbox or to increase the moment arm by increasing the size of the hub motors. The issues with these solutions are that with a gearbox, speed would be sacrifice and therefore not viable for an efficient transportation system. Although, it is possible in a scenario where an internal multi-speed gearbox is implemented, real estate space of the hub motor will increase drastically to make space for the gearbox. This leads us to a similar issue with the second solution of increasing the size of the hub motors, which will dictate the size of the wheels, resulting in inefficiencies in design, manufacturing, and cost. As mentioned earlier, to implement hub motors successfully, research and development into manufacturing custom high-power density hub motors is needed.

As SPARTAN Superway continues in evolving to become a viable source of transportations for densely populated cities, it is vital for the drivetrain team to experiment with various sources of motors and propulsion system to find what will best suit its need in scalability and function. In order to find this optimal source of propulsion, communications, and contributions from the various sub-teams are necessary. The optimal propulsion system is reliant on the design choices for guideway, bogie system, and wayside power. As such, it is beneficial to continue experimenting and testing out new configurations.

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19.0 Appendices

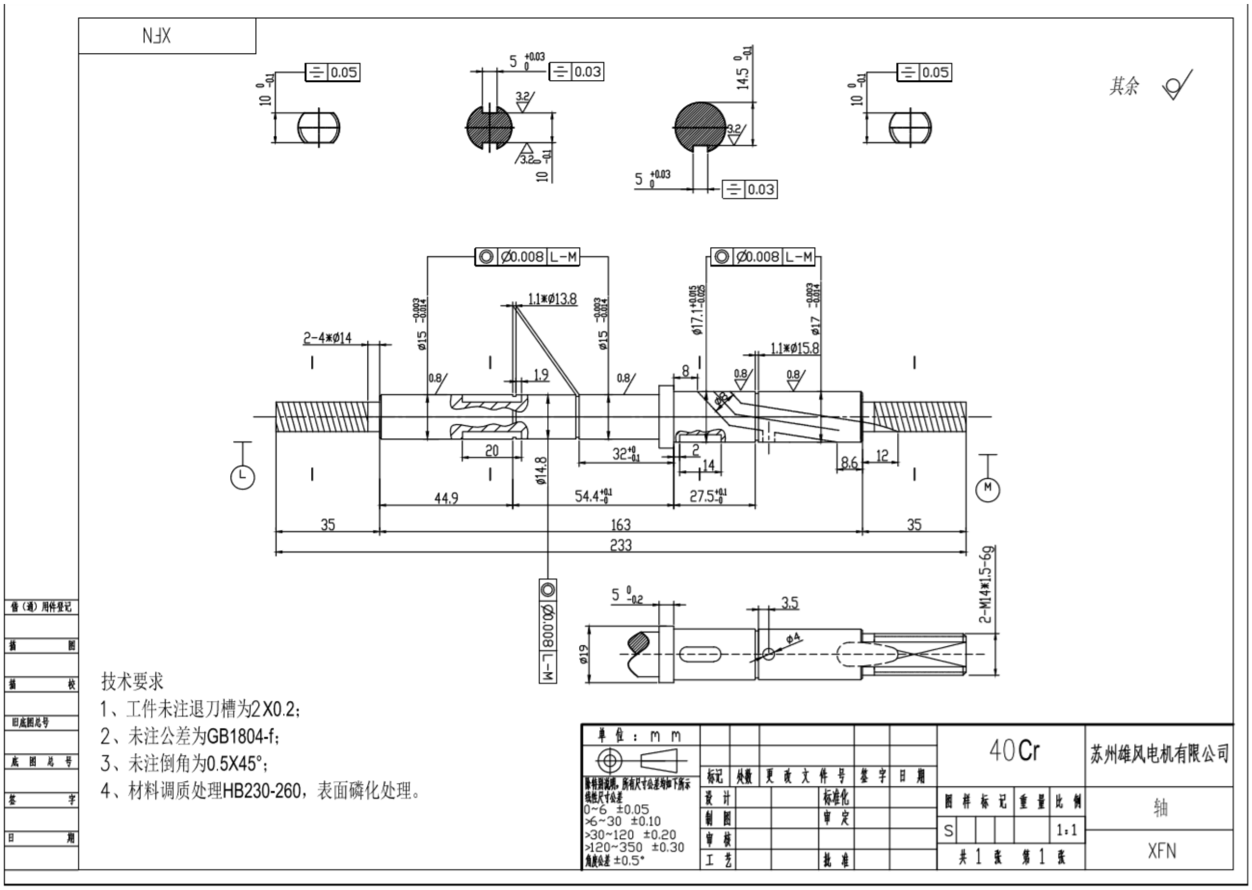

Figure 20: Motor Shaft Dimensions for XOFO’S SOFN Motor

Table 7: XOFO's SOFN Motor Specifications

Rated Voltage	48	**Stall Torque**	110 NM
Rated Power	750 W	**Rated/Continuous Torque**	53 NM
Rated Current	13-20 A	**Rated Speed**	90.9 RPM
Peak Current	25 A	**Rated Efficiency**	>=78
Reduction Ratio	1:6.9	**Hall Sensor**	Yes
Magnet Poles	30	**Weight**	4.9 Kg

Table 8: Kelly Controller's KBS48051X Mini Brushless DC Motor Controller Specifications

Kelly KBS-X Brushless Motor Controller			
Model	30 seconds Current(Amp)	Continuous Current(Amp)	Voltage(Volt)
KBS24051X	50	25	12-24
KBS24101X	100	45	12-24
KBS24121X	120	55	12-24
KBS36051X	50	25	24-36
KBS36101X	100	45	24-36
KBS48051X	50	25	24-48
KBS48101X	100	40	24-48
KBS48121X	120	55	24-48
KBS72051X	50	25	24-72
KBS72101X	100	40	24-72
KBS72121X	120	55	24-72
1.24V model: range of the max operating voltage is 8-30V. 2.36V model: range of the max operating voltage is 18-45V. 3.48V model: range of the max operating voltage is 18-60V. 4.72V model: range of the max operating voltage is 18-90V.			

Table 9: Equations and Formula Used to Calculate Hertzian Contact Stresses

Calculation for cylindrical contact
Contact half-width (b)
$b = \sqrt{\frac{2F}{\pi l} \frac{(1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2}{1/d_1 + 1/d_2}}$
Maximum pressure (p_{max})
$p_{max} = \frac{2F}{\pi b l}$
Principal stress (σ_x)
$\sigma_x = -2\nu p_{max}\left[\sqrt{(1+\frac{z^2}{b^2})} - \left\lvert\frac{z}{b}\right\rvert\right]$
Principal stress (σ_y)
$\sigma_y = -p_{max}\left[\frac{1+2\frac{z^2}{b^2}}{\sqrt{(1+\frac{z^2}{b^2})}} - 2\left\lvert\frac{z}{b}\right\rvert\right]$
Principal stress (σ_z)
$\sigma_z = \frac{-p_{max}}{\sqrt{(1+\frac{z^2}{b^2})}}$
Shear stress (τ_{xz})
$\tau_{xz} = \frac{\sigma_x - \sigma_z}{2}$
Shear stress (τ_{yz})
$\tau_{yz} = \frac{\sigma_y - \sigma_z}{2}$

Figure 21: Equations Used to Calculate Contact Stress