BOGIE DESIGN FOR A SUSPENDED SOLAR-POWERED ATN VEHICLE

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The Undersigned Committee Approves

Bogie design for a suspended solar-powered ATN vehicle

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ABSTRACT

Bogie design for a suspended solar-powered ATN vehicle

By Mohammed Owais I. Saiyed

Solar Powered Transit has the potential to reduce road traffic as well as the emissions of the greenhouse gases, by providing a clean, convenient, and fast transportation around the city. It is done by using solar powered ATN vehicles that rise above the street level for much faster and uninterrupted ride. SPARTAN Superway's current design for solar-powered autonomous transit system utilizes a slim guideway, which is above street level, an autonomous bogie that is attached to a cabin, which can fit about 4-6 people. Using a passive guideway allows the bogie to change tracks at the junctions. It does that using a switching mechanism, which is the highlight of this project. Looking at different commercial and relevant ongoing project designs for the switch mechanism and making improvements upon them. Also presenting a battery pack that uses 21700 form factor lithium ion cells, to power the bogie. Analyzing each component of the bogie in detail and performing finite element analysis to ensure that parts will not fail under maximum loading. Also, layout a plan for future improvements and manufacturing processes of the components.

ACKNOWLEDGEMENTS

I would like to acknowledge my committee chair Dr. Furman for providing helpful feedback on my bogie designs and guiding me towards a better and more stable design. I would also like to thank Dr. Furman for taking time off every weekend so we can go over the progress made over the week. I would also like to acknowledge the committee members Ron Swenson and James Mokri, and rest of the SPARTAN Superway team for providing feedback every week and pointing out better solutions to the problems. I would like to thank Liwei Lu for working alongside me for his guideway designs.

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1.0 INTRODUCTION

Most Americans rely on automobiles for transportation, so much so it is a big part of our culture. Typical 'American Dream' involves owning a house and a car. We do not like to be dependent on public transportation, and our government does not even support most public transportation projects, which is one of the reasons why we still don't have a high-speed rail system (Loukaitou-Sideris, Peters & Wei, 2015). Though cities like San Francisco and New York have amazing subway systems, cities like Los Angeles and San Jose residents have to be highly dependent on their automobiles. Though both cities have some sort of metro line and city buses they are very inefficient when compared to New York's subway system. We are trying to slowly move towards electric cars, like Tesla, but that mainly depends on how the electricity that you are using to charge your car is generated (Wills, 2014). Most of the electricity generated in the US is from fossil fuels ("U.S. Energy Information Administration - EIA - Independent Statistics and Analysis", 2018).

1.1 Fuel Dependency

The United States is heavily dependent on fossil fuels, and as we grow in population, the demand for fossil fuel will only increase. It's not just cars and transportation, a lot of states still use fossil fuels to generate electricity ("U.S. Energy Information Administration - EIA - Independent Statistics and Analysis", 2018). The biggest problem with being dependent on fossil fuels is that it will eventually run out. Fossil fuels are not renewable and there is a limited amount of it on this planet (Oliver & Manne, 1976). In terms of Fossil fuel usage, 28% of all fossil fuels are used for transportation (Wills, 2014, p.10).

1.2 Traffic

Americans being dependent on their cars not only hurts the environment, but it also creates another bigger problem, traffic. A large number of cars on the road during rush hours leads to traffic jams and automobile accidents (Norman, 1998). We do have monorails on city streets, which only adds to the road traffic. Monorails take up huge spaces on the road and makes frequent stops, which creates more traffic. Subway system is a better solution to this problem because they are underground, therefore they don't add to the road traffic, but digging tunnels underneath the city is very expensive and time consuming. One of the better solutions to all of these problems is Solar Powered Automated Rapid Transit Ascendant Network (SPARTAN) Superway project. SPARTAN Superway project will help cut down travel time, and greenhouse gas emissions, while reducing the cost for transit (Furman & Swenson, 2019). Autonomous driving is gaining more popularity each day, it is expected that in the next 50 years the majority of vehicles on the road will be partly autonomous (similar to Tesla's self-driving package) (Niles, 2019). It is time our transit systems also moved in that direction.

Figure 1:- Solar-powered automated transit (Hagstrom et al., 2017). Relatively small vehicles used on a slim guideway to provide non stop travel utilizing offline stations.

1.3 SPARTAN Superway

SPARTAN Superway is solar-powered automated rapid transportation, which is designed to rise above the street level, so it does not add to the road traffic (shown in **Figure 1**:- Solar-powered automated transit (Hagstrom et al., 2017). Relatively small vehicles used on a slim guideway to provide non stop travel utilizing offline stations.). Solar panels are placed on top of the track to collect energy needed to run the system. Unlike a monorail, which can fit about 75-79 people at a time and runs every half hour (Benjamin, 2019, 14), a SPARTAN Superway vehicle is designed to take only about 4-6 people at a time. With that rate and a headway, which is distance between two vehicles measured in seconds assuming they are both moving in same direction and at constant speed, of about 10 seconds and speed of 25mph it can transport about 1,400 people per hour, that is 7 times more compared to monorail (assuming 2 monorail per hour). Passengers will be able to pick the station they want to get off at and the bogie will only stop at that particular station. This can be done with the use of 'offline' stations, where a junction in the track will allow the vehicle to split off the mainline and stop at the station (shown in **Figure 2**:- Solidworks model of SPARTAN Superway track designed by 2014-2015 students showing offline stations on a guideway (Ornellas, 2015).) so there are no intermediate stops along the way. This is set in place so passengers who are traveling further will not have to wait for vehicles that are stopping at a station ahead.

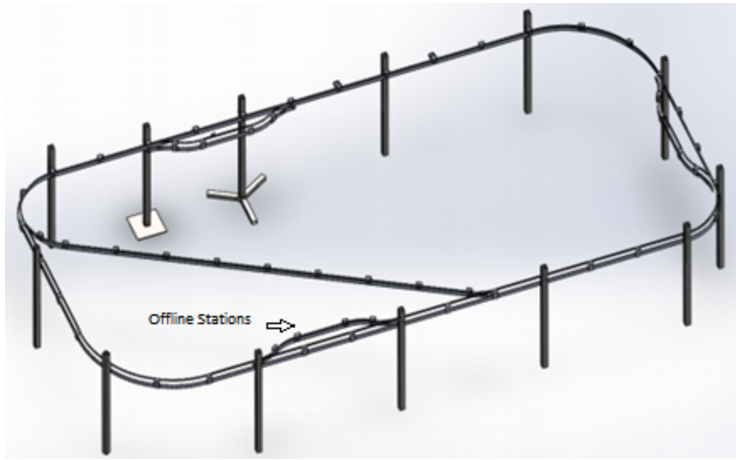

Figure 2:- Solidworks model of SPARTAN Superway track designed by 2014-2015 students showing offline stations on a guideway (Ornellas, 2015).

The vehicle must have a mechanism in its bogie, which sits on the guideway and includes a propulsive wheel assembly that moves along the guideway to help the vehicle change tracks at junctions shown in **Figure 3**. This is a very important mechanism because when it switches the track there is a chance of passengers feeling a nudge or possible de-railing of the bogie. The key is to have the bogie move through the junction without falling off the guideway. It will also have sensors in the front and the back of the bogie so it can detect other bogies to avoid crashes.

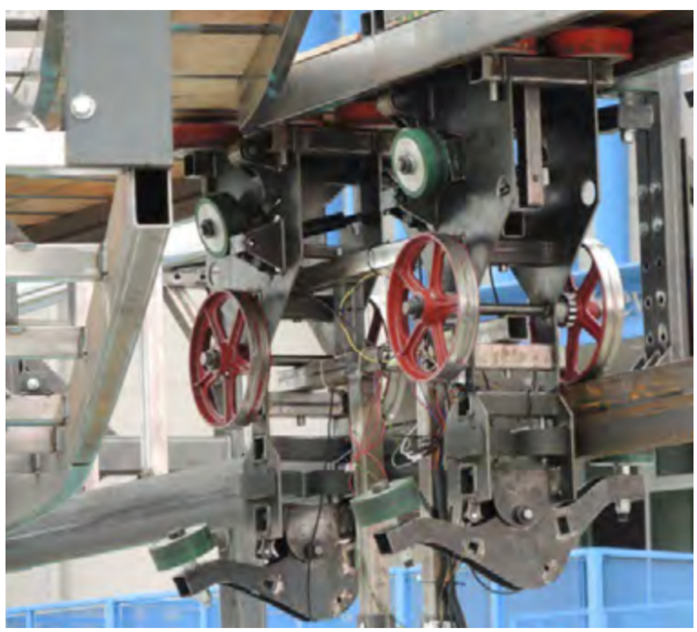

Figure 3:- Bogie with a steering mechanism on a guideway junction shown at Maker Faire 2015 (Furman, 2016).

2.0 OBJECTIVE

The main objective of this project is to design a bogie for Spartan Superway from which a passenger cabin is suspended below, which will allow the bogie to take one path or the other at a junction on the guideway. This project is in conjunction with another project by Liwei Lu, who is working on the guideway that supports the bogie and cabin system. It is important to note that the track is entirely passive unlike a typical rail vehicle, but rather the bogie mechanism has movable elements that make the selection of one or the other paths through the junction. Designing a switching mechanism that will enable a suspended cabin to reliably move through a passive guideway junction.

3.0 METHODOLOGY

1. Conducted a review of the literature including patents, reports, and other approaches for vehicle switching. I will consider multiple designs (shown in the literature review) and make further improvements for a smoother and safer ride for the passengers.
2. Design a bogie in conjunction with Liwei Lu's guideway.
    a. Guideway is passive so I need to design a mechanism to switch tracks at junction.
    b. Make a bogie frame so it can be attached to a cabin.
    c. Introduce a suspension system to reduce the vibrations in the bogie and cabin.
    d. Design a battery pack that provides sufficient voltage and capacity for the system.
3. Making improvements on the previous designs and coming up with a better switching mechanism design.
    a. Combination of H-ban switching Mechanism and Bill's approach to the switching mechanism.
4. Battery Modules
    a. Using 21700 form factor batteries, I designed two separate battery packs for with different voltage outputs. One is high voltage pack for commercial use in the near future and second is lower voltage pack for safety during the prototype construction.
5. Estimate the loads that will be acting on the bogie. For example: the dry weight of the cabin, weight of the passengers (and any luggage they might be carrying) inside the cabin
6. Bogie Frame
    a. Designed a bogie frame out of standard size steel tubing.
    b. Making the frame design accommodate the switching mechanism and using the frame as a supporting structure to the switching mechanism.
    c. Frame is designed to fit the battery pack on the bogie itself, to keep the cabin weight to a minimum.

   d. Accounted for the suspension system on the bogie itself since the battery pack is now placed on the frame of the bogie.
   e. Horizontal wheel placements to keep the bogie from going off track.
7. Finite Element Analysis (FEA) of the bogie
   a. Static analysis on the bogie frame accounting for the forces that will be exerted on the bogie
   b. Using SOLIDWORKS to do FEA simulations to find the deflection, stresses and factor of safety.
8. Motion Analysis of the Bogie with dummy Track
   a. Building a dummy tack that reflects the actual track contact surfaces. This will reduce the mesh size and will reduce the simulation time.
   b. Setup contacts between bogie parts and the track. For example, setting up kinetic friction and static friction values between rubber tires and steel track.
   c. Adding springs and dampers to replace suspension parts.
   d. Adding motors and assigning correct direction and RPM for them.
   e. Running the simulation and setting up monitors to check the reaction forces and obtain the magnitude of reaction forces on various components with respect to time.
9. Thermal analysis for water-cooled battery pack
   a. 2D CFD for one water channel to check the temperature difference in cells near inlet and outlet.
   b. Static thermal analysis.
   c. Transient thermal analysis.
   d. Static structural analysis under thermal loads.

4.0 LITERATURE REVIEW

Following Literature review provides background information about ATN vehicle systems that are already operating commercially, relevant ongoing projects, and prior work done by SPARTAN Superway teams. It also provides detailed information on some of the switching mechanisms used to change direction of the bogie as well as suspension and battery cooling system that can be implemented.

4.1 ATN System

There are companies like ‘Futran Systems’, who are working on a suspended vehicle from a bogie on a passive track to transport goods and people in developing parts of the world (“The Future of Transportation Is Now the Present”). They have fabricated a prototype and tested it on a 1km track in South Africa, and they are working on a similar design to transport people around town. Another example of a similar project is the Cabintaxi from the University of Washington. They designed a couple of different vehicles, one for 3 passengers and the other one was to fit about 12 passengers (Cabintaxi PRT System, 2012). They also have a similar idea of ‘origin to destination operation’, with the utilization of ‘offline stations’, so there will be no intermediate stops along the way. They are using linear induction propulsion to control separation between the two vehicles keeping them about 10 seconds apart from each other (minimum headway), which gives the bogie enough time to either slowly make a stop or choose to turn if there is a junction available (Cabintaxi PRT System, 2012). These vehicles could travel at speeds of 22mph, which is exactly what we are looking for.

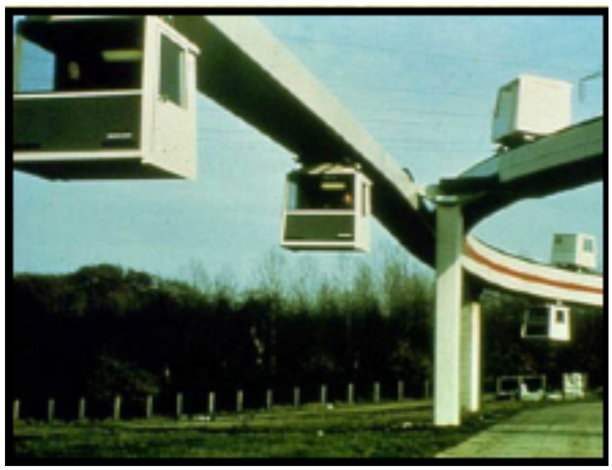

Figure 4:- Cabintaxi PRT (Personal Rapid Transit) system (Cabintaxi PRT System, 2012).

We see similar designs in the book ‘Fundamentals of Rapid Transit’. Instead of a monorail that can fit about 100 people, they made the vehicles smaller and have them run more often. This turns out to be more efficient (Irving, 1978, p.16). They also came up with **Equation 1** to calculate the minimum headway in seconds that we need.

$$H = \frac{L+S}{V} \qquad (1)$$

H: minimum headway in seconds
L: Length of vehicle
V: Vehicle Speed
S: Minimum allowable separation while traveling at speed V

Using this equation, we can calculate the headway space in seconds, so we give the bogie enough time to either slow down and come to a stop or turn if there is a junction available.

4.2 Switching Mechanism

Switching mechanism is used to guide the bogie into the correct track at junction. Switching mechanism patent by Gustafsson uses the passive track to its advantage. As we can see in **Figure 5** below, the track is designed with cutouts at the junctions. This helps the bogie maneuver the junctions without derailing (Gustafsson, 2014). It has the switching mechanisms on its sides, which can open or close depending on the direction of the turn. The bogie also has switching mechanisms on the top to prevent it from toppling over. The downside of this bogies is that it does not have anything to counter the weight of the vehicle due to gravity. If we suspend a cabin to this bogie it has no wheels or anything laying on the track to counter the loads. It's only designed to be a switching mechanism on the passive track and nothing more.

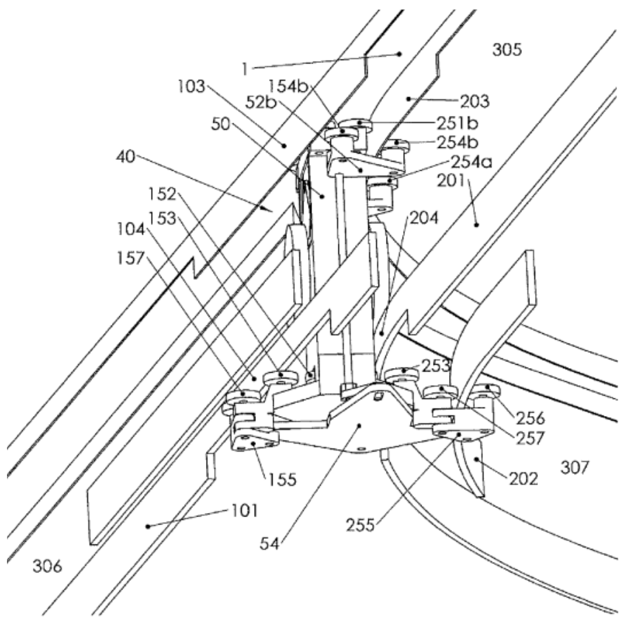

Figure 5:- Bogie for a suspended ATN vehicle in a guideway junction (Gustafsson, 2014).

Another good design for the switching mechanism is used in the H-Bahn suspended monorail system (Siemens H-Bahn – Switching, n.d.). In their system they are using a four-bar linkage with a pivot and wheels at the ends to switch tracks at the junction. **Figure 6** shows the switching mechanism on the H-Bahn bogie, we can see that the pivot point tilts one side of the linkage down so the wheels that are attached at the end can hook inside the slot that is already built on the track.

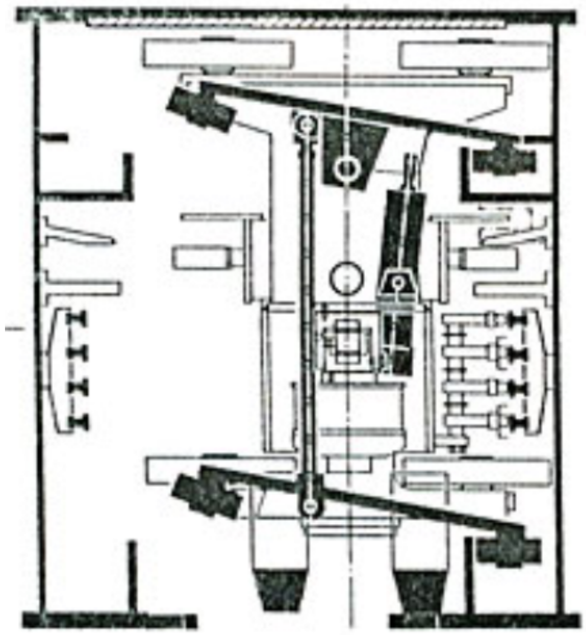

Figure 6:- H-Bahn Switching Mechanism utilizing a linkage system (“Siemens H-Bahn – Switching”, n.d.)

This is a very effective design, especially because there are multiple spots where the wheels from the switching mechanism are making contact with the track. This is very effective because it acts as a safety feature in case the linkage breaks at least one of the wheels will hook inside the track preventing possible derailing of the bogie. Another huge advantage of this design is since it has two points of contact the load in each linkage is divided by half, similarly the loads on the small bearings inside those wheels will be divided by half, which is a huge advantage. The downside of this design is during the junction when one of the wheels is not on the track the bogie will experience counterclockwise moment (based on **Figure 6** shown above), and this can possibly tilt the bogie downwards. To prevent this, they added a small bar on top of the wheel, to prevent the wheel from coming out of the track when the bogie tilts. This does counter the moment that can tilt the bogie, but it can also damage the wheel that is hooked inside the track, the wheel will contact the bar and exert force on it to counter the moment, this can possibly break or badly damage the guiding wheel that is hooked inside the track.

There are some concept designs from the work done by other students in previous semesters (2016) at Spartan Superway. The switching mechanism design shown in **Figure 7** consists of red wheels, which rest on the track supporting the weight of the vehicle, the green wheels on the sides on top and bottom of the bogie are the witching mechanisms. On the junctions the track has a small gap so the bogie can make turns with the suspended vehicle underneath, this causes the red wheels to be in the air while the bogie is making the turn (Acoba et al., 2016). In order to prevent derailing the green wheels holds on the tack on the top and bottom. The yellow wheels in are present to keep the bogie on track and it constrains the movement in the left and right direction.

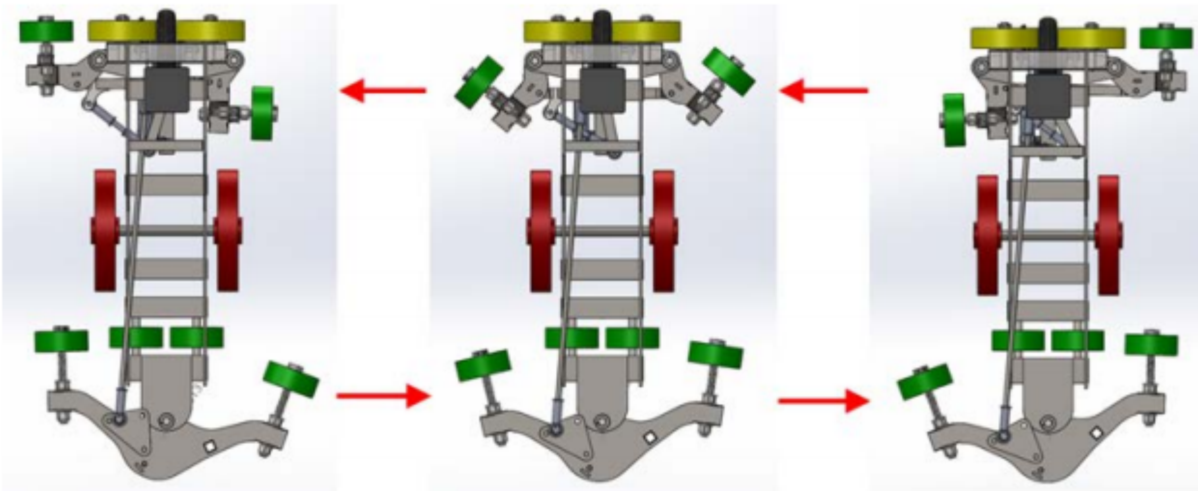

Figure 7:- Steering mechanism for bogie using guide rails as support (Acoba et al., 2016). Full assembly along with the guideway is shown in Figure 3.

Another design has a much simpler mechanism with one arm with a servo motor, which moves left and right turning the bogie in the correct direction (shown in **Figure 8**). This is a very simple mechanism, which allows the bogie to change track with just one simple move. Similar to the previous design at the junction one of the wheels that is taking the weight of the vehicle is hanging in the air, to counter that the switch is touching the top of the track with a wheel, which can provide support and prevent it from derailing. The downside to this is when the arm switches from left to right, it makes a loud noise and the passengers inside the cabin will hear the noise. Also, when the bogie turns, one out of the four wheels is in the air and lands back on the second track, which can lead to the passengers feeling a nudge when the wheel goes from air to the next track.

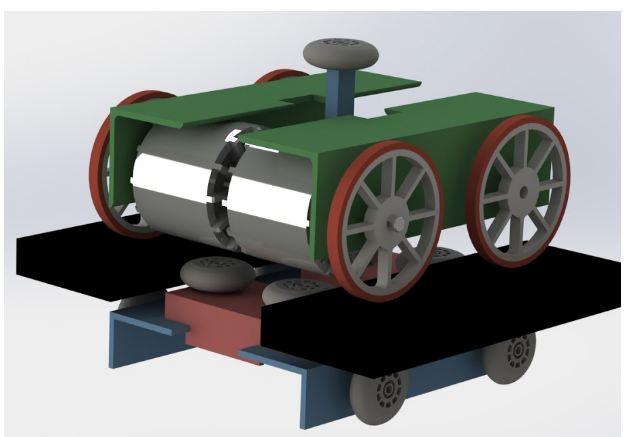

Figure 8:- CAD for alternate bogie with switch mechanism on top. (I got this CAD model of the bogie from Bill when I visited Spartan Superway Design Center)

One of the older designs used a supercapacitor to charge the bogie on the stations really quickly and use that charge to get the bogie moving at about 25mph, once the capacitor has released all of its charge the bogie will run onboard batteries (Coaquira et al., 2019).

4.3 Bogie Frame & Suspension

Along with the switching mechanism H-Bahn also have a good frame design for their bogie. They have guiding wheels on the top and bottom of the bogie to keep the bogie centered on the track, this provides stability and decreases the chances of derailing. Another thing to notice in this design is that they are using standard structural tubing to build this frame. This cuts down the manufacturing costs, because instead of machining new parts you can just buy standard tubing and weld them together to build the frame.

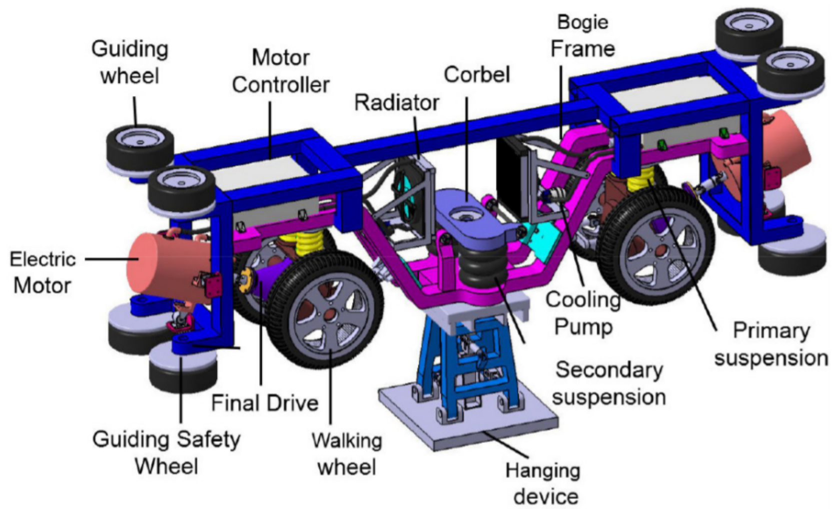

Figure 9:- H-Bahn Vehicle Frame (Zhang, 2017). Shows CAD model of bogie frame with all the components

From **Figure 9**, we can see that the frame is built out of standard size tubes just welded together, in addition to that this frame also accounts for spacing for motors, motor controllers, radiators, and suspension for both the bogie and the cabin (Zhang, 2017). They kept the space where the bogie attaches to a minimum, because that defines the gap in the track at the junctions. The way they have the bogie suspensions set up is also very efficient, they realized the when one of the wheel is not on the track at the junction the suspension can expand all the way and the wheel can bang on the track on the other side. To avoid this, they placed the suspension in the middle and is connected to both wheels simultaneously, this prevents the suspension system to expand all the way because one wheel is still keeping the suspension compressed. Unfortunately, they do not have any space dedicated to a battery pack on the bogie itself. Another downside to this frame is that both radiators are in the middle of the bogie, and are facing each other, this is not very efficient for cooling. It would be much more efficient if they moved the radiators in the back and the front of the bogie so when it moves, the fresh air can blow right in the front of the radiator.

SPARTAN Superway class of 2016 came up with their own design for the suspension of the cabin. **Figure 10** shows the assembled bogie on the guideway, and we can see there are three shock absorbers coming out from the bogie and connecting in the middle, which is where the cabin will be attached. This provides smoother ride for the passengers inside the cabin and at the same time keeping the cabin stable. This design does not have any suspension on the bogie itself, that is probably because they do not have any major components like a battery pack on the bogie itself. We would like to put the battery pack on the bogie itself to minimize the cabin weight, therefore we will need to have suspension on the bogie, so the pack does not vibrate.

Figure 10:- SPARTAN Superway Bogie Assembly Class of 2016 (Acoba et al., 2016). Utilizing three shock absorbers to hold the cabin doubles as suspension.

4.4 Battery Module

Companies like Tesla have made their mark on the electric vehicle industry, one of the major contributors to their success is their battery design, they make some of the best battery modules, and with correct placements on their vehicles. They place their battery pack at the bottom along with the car chassis, this lowers the center of gravity of the vehicle and provides better control over the turns. We can take a look at battery modules that Tesla uses in their vehicles and figure out a way to adapt that design to work with our bogie. Tesla has used different types of batteries over the years, including 18650 and 21700, which is a cylindrical battery with 21mm diameter and 70mm length, similar for the 18650. Recently they announced new battery form factor 4180, which is 41mm in diameter and 80mm tall. Tesla claims that these batteries will increase the power by factor of six and increase the capacity by factor of five (Lyons, 2020).

Figure 11:- Tesla's Model S Battery Module with Thermal Management System (Albright, 2018)

Looking at Tesla's battery module shown in **Figure 11**, we can see that the 18650 cells are held together by the pipes, which are used to cool the cells. Each module has one inlet and one outlet, we can see that the cooling pipe is touching at least one surface of the cell so they can manage the temperatures of the cells. This battery module gets a huge benefit from using the pipes to hold the cells in place, it serves the purpose of keeping everything in place and provides thermal management.

4.5 Battery Thermal Management System

All batteries start to lose capacity as they are charged and discharged multiple times. The temperature at which the batteries are stored and operated along with the charged storage capacity plays a huge role in determining the life of the battery. **Figure 12** shows the relationship between the storage capacity (SOC) and time. As we can see they have two separate analyses, one with batteries with 50% charged to full capacity and one with 100% charged to full capacity. We can see that the batteries that are charged and stored at full capacity will lose capacity faster compared to the ones only charged to 50%. Also, notice that the cells kept at lower temperatures last much longer compared to the ones kept at a higher temperature. Therefore, it is beneficial to introduce a thermal management system to the battery pack so the batteries can stay close to their original capacity for much longer.

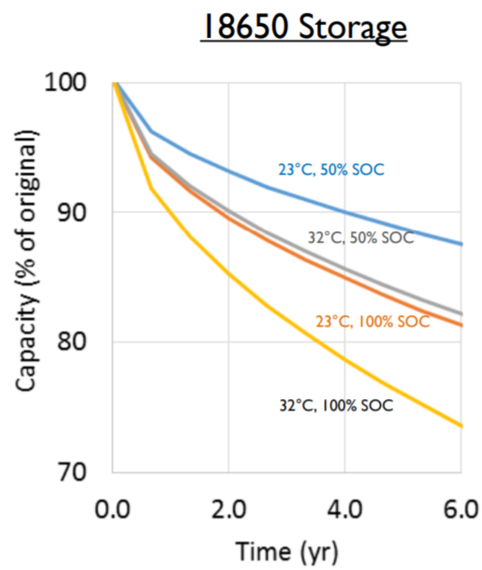

Figure 12:- Capacity percentage of 18650 Battery Vs. Time in Years (Albright, 2018)

Newer Tesla cars (Model 3 with heat pump) changed their cooling system from the one we see in **Figure 11**. The battery module shown in **Figure 11** has one inlet and one outlet for the whole module. The problem with this design is that as the water flows through the water channels it absorbs heat from the cells and therefore the cells by the inlet and the outlet will have a much higher temperature difference. **Figure 13** shows the updated design for the Tesla Model 3 battery pack. This battery pack has multiple channels and they all flow in the same direction rather than looping back and forth (Bower, 2019). This will result in a lower temperature difference between inlet and outlet. We want all cells to be close to the same temperature so as they lose capacity evenly and we don't have to worry about changing half the cells in a pack, which would be very hard to do depending on the battery pack design since most cells are welded on.

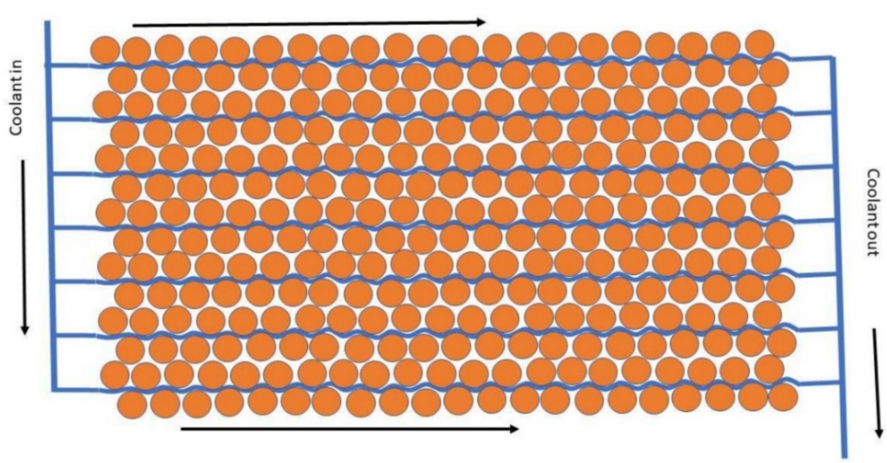

Figure 13: Updated Model 3 battery pack thermal management system (Bower, 2019).

5.0 DESIGN CONCEPT

5.1 Frame Assembly

We can see how all the parts come together in the assembly shown below, the switching mechanism is attached to the pivot at the bottom so it can swing left and right and can rest on the Aluminum support block. Bogie also takes advantage of an active air suspension system that holds the battery and the cabin. Since the battery pack is placed on the bogie I wanted to reduce the vibrations on the battery pack, the best way to do that was to add the battery pack to the same suspension system as the rest of the cabin. The battery pack is constrained using an aluminum plate and brackets on each side of the pack.

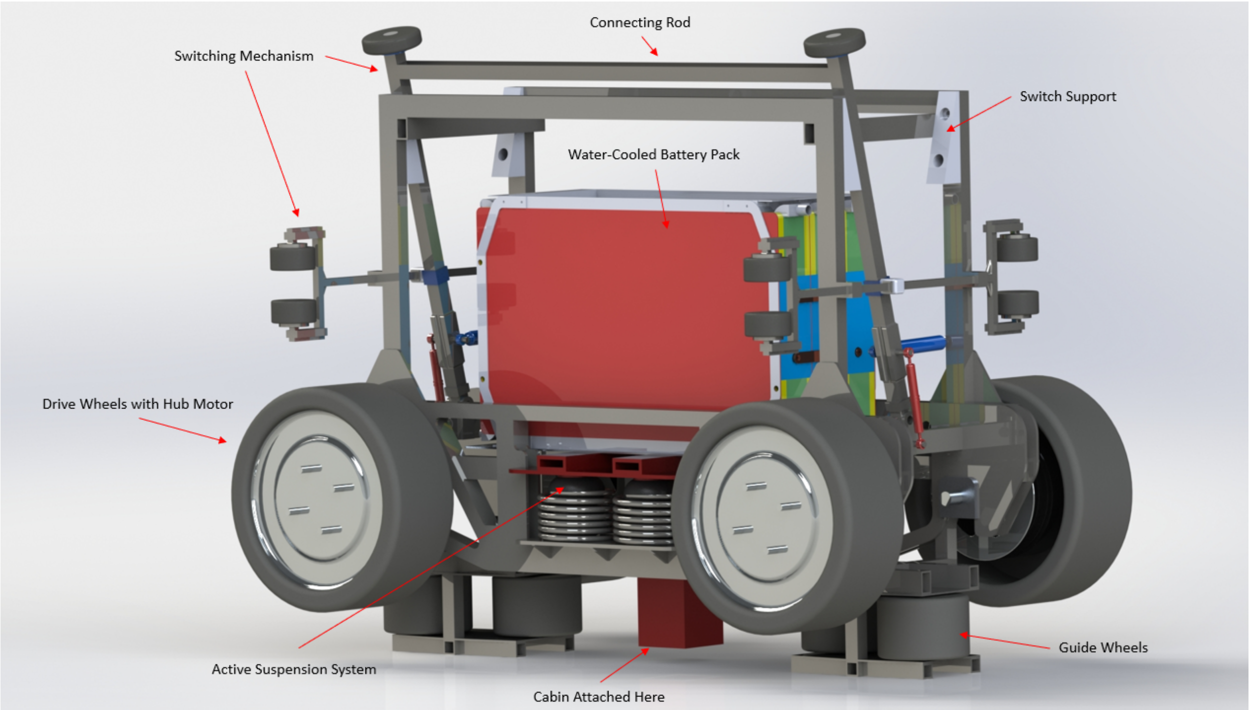

Figure 14:- Bogie assembly with all major components

Figure 15 shows the front view of the bogie assembly on the guideway, which is designed by Liwei Lu (Lu, 2020). We can see that the horizontal guide wheels at the bottom are used to keep the bogie centered on the track. The vertical switch bar can swing left or right depending on which side it is going to turn. Liwei also used I-beams on the side of the track to hook in the side switch wheels. These side switch wheels help the bogie turn and prevent it from tilting on the turns. Since our suspension only affects the battery pack and the cabin, we did not have to leave a lot of wiggle room for the top wheel and the side wheel engagements with the track.

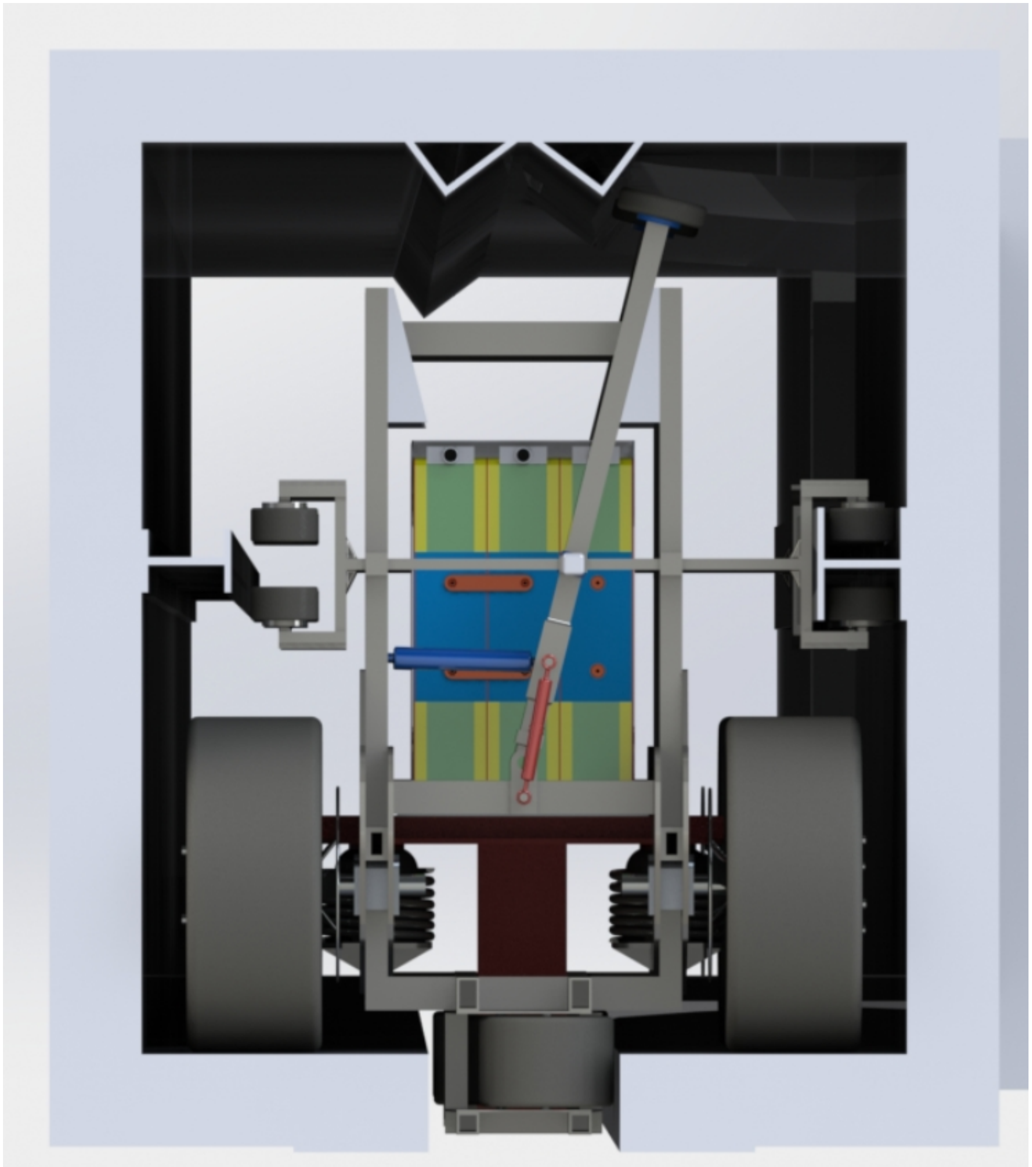

Figure 15:- Front view of the bogie assembly inside the track junction (Lu, 2020)

5.2 Switching Mechanism

The most important part of this project is the switching mechanism. We need the bogie to be able to switch track on junction without derailing. The track will be completely passive, we need the bogie to have a mechanism that can guide the bogie into the correct path. During this process, one side of the bogie wheels will go over a gap and the switching mechanism will need to carry the load and transfer it to the frame. Therefore, the switching mechanism needs to be able to counter the moment that is generated by the two bogie wheels not being on the track.

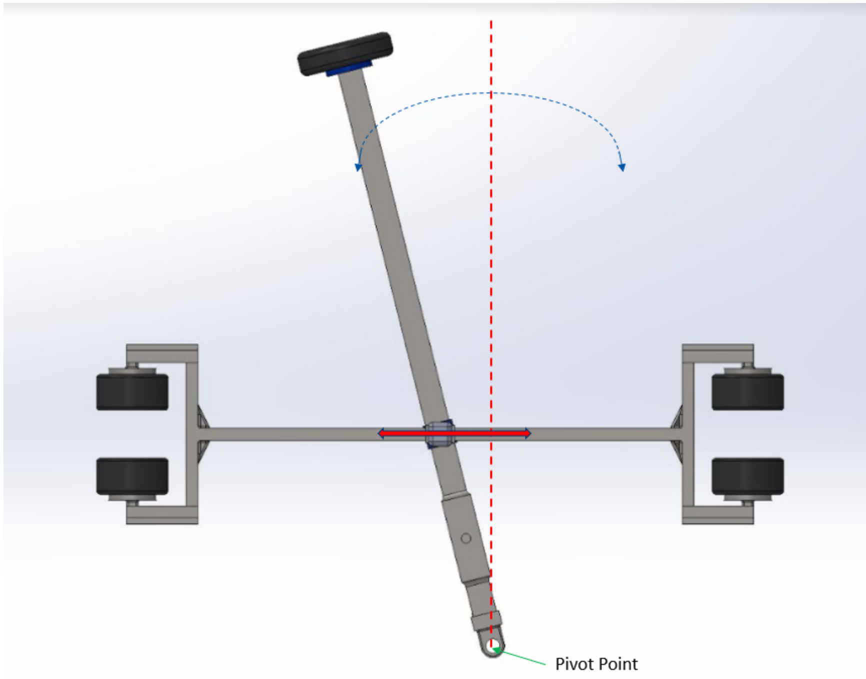

Figure 16:- Switching mechanism assembly

Figure 16 shows the CAD model of the switching mechanism assembly. The vertical bar tilts left or right about the pivot point dragging the horizontal sliding switch with it. This motion determines the direction of the bogie before it enters any junctions on the track. The wheel on the vertical bar is a 4" diameter heavy-duty polyurethane caster wheel, the bar is made from structural steel 1" tubing. On the other hand, the sliding switch is made from ½" structural steel tubes. The smaller wheels attached to the sliding switch bar are 3" in diameter and they hook into I-beam on the track to guide the bogie on the correct path.

We can see the whole assembly in **Figure 15**, the switching bar is resting on aluminum support, which is connected to the bogie frame. This support block transfers the load from the switch bar into the frame. Notice the wheel on top of the switch bar contacting the guideway and the slider switch wheel on the side is hooked into the I-beam, which pulls the bogie into the correct track.

To move this switch as it pivots left to right, I am using a hydraulic linear actuator, which is shown in **Figure 17** color coated in blue. This actuator will control the movement of the switch, we can use this to control how fast the switch can move from left to right, tuning the speed of the switch to reduce noise. I also decided to use a stretched spring shown in red to prevent the switch from staying in the middle. The spring is stretched when the switch bar is in the vertical position and since the spring naturally wants to compress to go back to its natural state it will put the switch bar towards either side of the frame. This is used as a fail-safe mechanism, because the way this switch is designed the bar must be on either left or the right side, if it fails to be on either side, we expect major failure in the system

.

Figure 17:- Bogie switch mechanism is controlled using a hydraulic linear actuator and a stretched spring is used as a fail-safe.

5.3 Switch Bar Support

To support the switching mechanism and have good contact with the frame so it can transfer some of the load to the frame, I had to make a support structure out of aluminum. The rest of the frame is made from steel but since this supporting structure is going to only face compression and in only one direction, I decided to use aluminum, which is much lighter compared to steel.

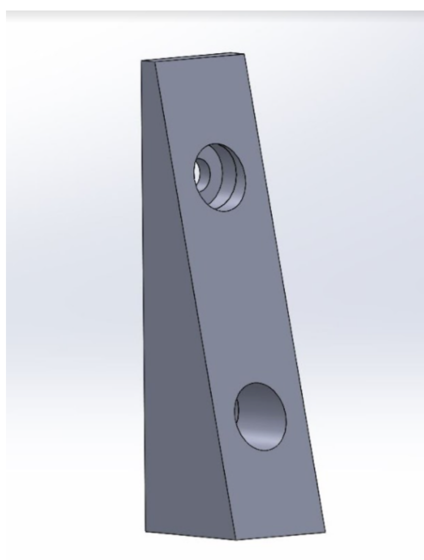

Figure 18:- Aluminum switch bar support with M8 bolt counterbores.

This support is attached to the frame, which is mostly made up of structural steel tubes, so to constrain this on the frame I decided to use screw-to-install rivet nuts. **Figure 43** in the appendix shows a screw-to-install rivet nut. This will allow us to drill a hole in the tube and fit the screw-to-install rivet nut into the tube, once installed we can use an M8 bolt to screw on the aluminum support in place.

5.4 Bogie Frame

The bogie is designed such that its suspended cabin can fit 4 to 6 people with luggage, and we also need to account for the dry weight of the cabin itself. With each person weighing around 75Kg on average, and each of them with luggage of 23Kg (I am using 23Kg for the luggage weight because that is the maximum weight of a bag allowed for air travel without any charges). This gives a total weight of the passengers and their luggage to be at 588Kg. On top of this, I am adding another 400Kg for the dry weight of the cabin. The battery pack will be stored on the bogie itself so the weight of the cabin can be kept to a minimum. I am designing this frame for the total weight of the passengers, their luggage, and the cabin itself to be at 1000Kg. I will also need to account for suspension on this frame, since I plan on putting the battery pack on the bogie itself, I will have to put some sort of suspension system to prevent the bogie from vibrating too much. I also need this frame to accommodate the switching mechanism, which is one of the most important parts of this project, as well as act as a support for the switch. It will also need some horizontal wheel placement to keep the bogie at the center of the track and prevent it from derailing.

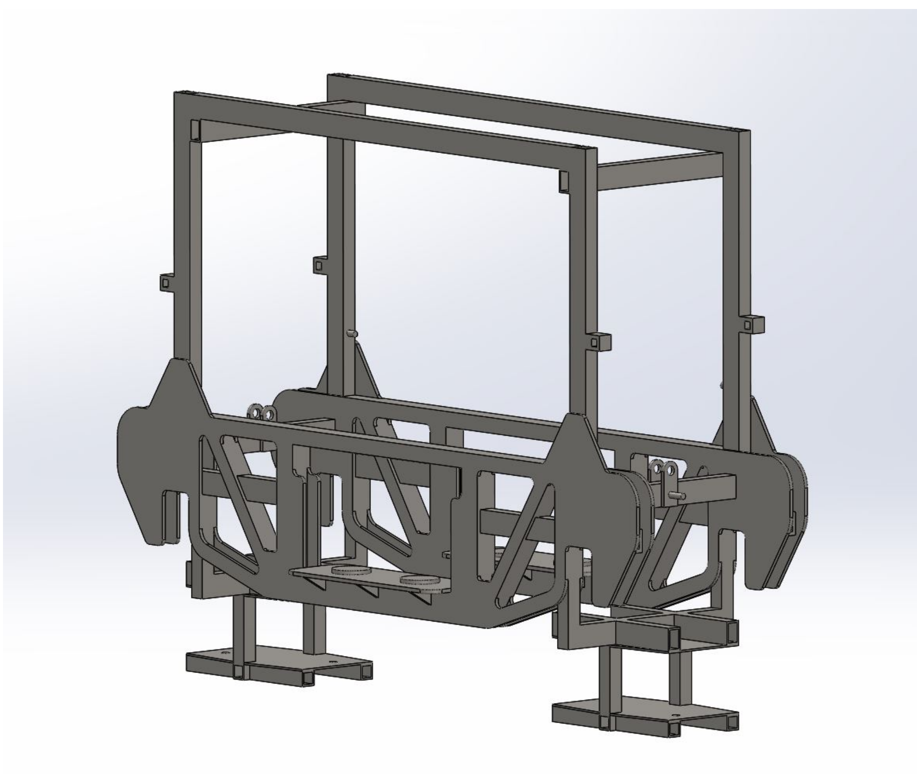

Figure 19:- CAD model of bogie frame.

Looking at the **Figure 19** above, we can see that the main components of this frame are the side plates that are attached to a bunch of steel tubes to add stiffness to the frame. The bogie is made from AISI 1020 Steel and weighs close to 90Kg. In the middle of the bogie is what the active air suspension is attached, which will be carrying the cabin and the battery pack. I have horizontal wheels placed at the bottom of the frame to keep the bogie from derailing. These wheels had to be close as close to each other as possible to allow the bogie to maneuver a smaller radius on the track, which is why instead of having two horizontal wheels side to side as shown in **Figure 44** in the appendix, I had to move them back and forth with an offset. I also have two horizontal bars that connect to the switching mechanism, these are 0.25" thick tubes. Four vertical bars coming up from the frame are supports for the switch mechanism, they transfer the load from the switch to the frame.

5.5 Bogie Suspension

The suspension system for the bogie consists of active air suspension and passive variable spring as a fail-safe, so in case there is an outage and the air suspension starts to lose all the air the springs can temporarily keep the bogie cabin from a hard step-down. We can also use sensors to cut off all power from the bogie drive train if the backup spring suspension is engaged, we can do that by placing a contact sensor at the lowest height we can afford to keep the suspension. This way the bogie will be stopped and will not damage any components by driving without suspension.

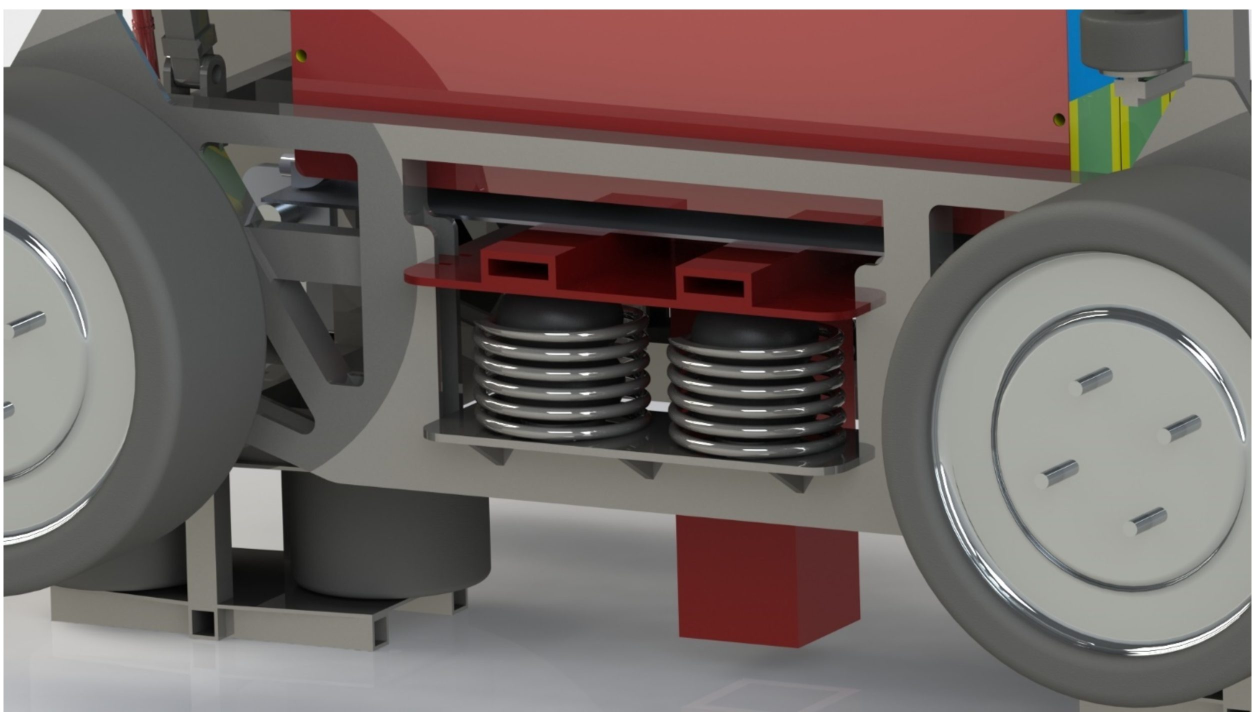

Figure 20:- Active air suspension along with a variable spring used as a fail-safe.

5.6 Battery pack

For this project I have designed two configurations for battery packs, one is a high voltage, which can provide close to 270V, and another lower voltage pack, which can provide half of the high voltage pack 135V. Each pack contains 1,152 cells. The cells I am using are 21700 cells, which means they are cylindrical cells with a diameter of 21mm and length of 70mm, each of these cells can provide an optimal voltage of 3.8V and capacity of 5000mAh. This pack consists of three modules which are connected in series. For the high voltage pack, each module has 16 cells connected in parallel and 24 series connections in each module. Similarly, the low voltage pack has 32 parallel connections and 12 series connection, which gives us half the voltage of the high voltage pack.

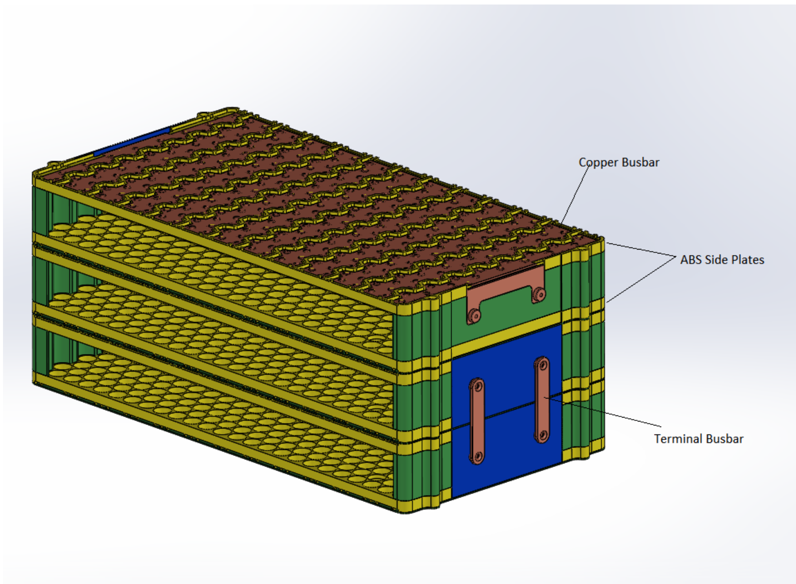

Figure 21:- 21700 High voltage battery pack assembly.

Each module consists of two ABS side plates, which is where the cells are placed, as well as a brace on each end of the panel to prevent it from crushing the cells. On top of the side panel we have copper plates which connects the cells together, and at each end of the panel is the copper terminal busbar, which connects multiple modules in series. There is a G10 sheet between the modules just so the copper plates do not touch each other.

The side plates shown in **Figure 21** are machined from ABS plastic, it is a complicated part to machine, it also has countersink M5 holes as well as some positions for locating pins to secure the brace, which is shown in green. The yellow plates also have spacers between copper plates because for safety purposes, especially for high voltage pack we do not want the copper plates to be touching each other or have any metal part short the copper plates.

5.7 Water Cooled Battery Pack

Water-cooled battery pack is very similar to the one mentioned above, it has the same number of cells, capacity and voltages. In order to keep the cells at lower temperature I added cooling channels through the pack as shown in **Figure 22**. For each module I have two inlets and two outlets, so for the whole battery pack there are six inlets and six outlets. Having more inlets and outlets gives us better flow and allows us to run the water pump at lower pressure. For this pack I am running the water channels between every other row of cells, so the water channel makes contact with at least one surface of each cell. This configuration is similar to the Tesla Model 3 configuration shown in **Figure 13**. I have also added thermal pads next to the channels so there we can account for any tolerance issues we might face, and to ensure we have good contact with every cell in the pack.

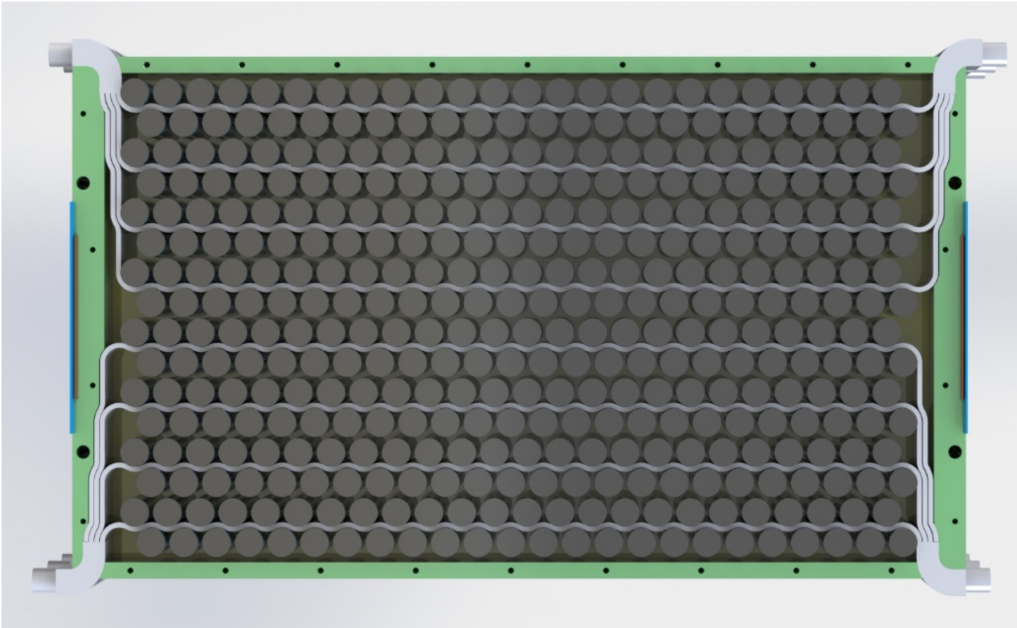

Figure 22:- Top view of water-cooled battery pack module, with two inlets and two outlets.

Another huge advantage of having a water-cooled battery pack is that I can have the whole pack enclosed, so no debris can get inside the pack. This is critical in our case because the battery sits on the bogie itself, which is running in an enclosed metal track, rather than inside the cabin. The metal bits from the track could potentially get into the battery pack creating shorts, which I would like to avoid at all costs.

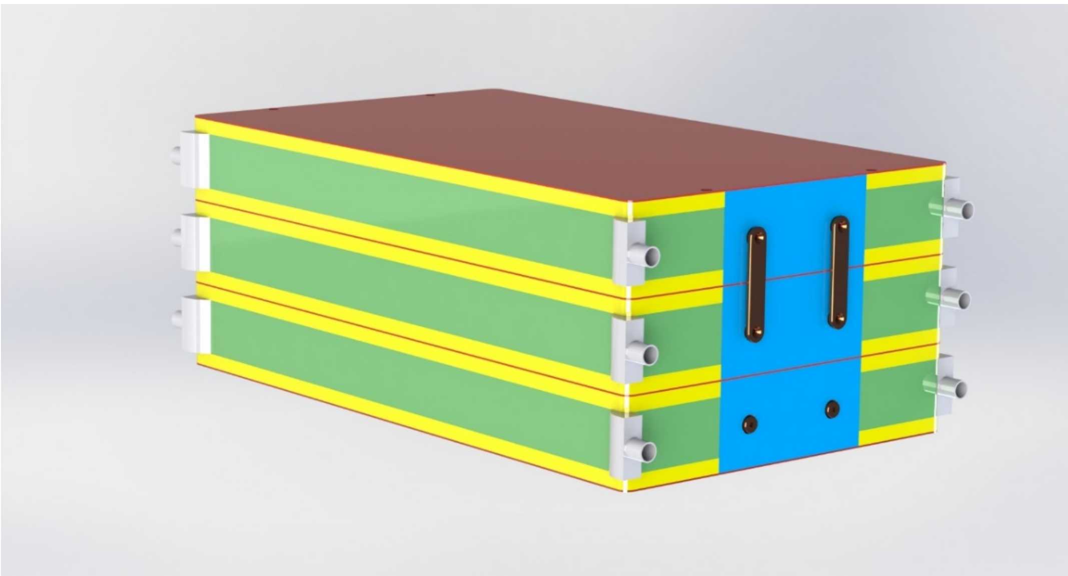

Figure 23:- Isometric view of all three battery pack modules assembled.

6.0 MOTION ANALYSIS

To find out exactly how much forces were going to act on each component, I decided to simulate the motion of the bogie running on the track using Motion Analysis tool in Solidworks. Motion Analysis allowed me to setup a dummy track, assign forces and contacts for different components and add motors to simulate motion. It also allows us to calculate reaction forces on each component at any given point of the simulation.

6.1 Motion Analysis setup

I started the motion analysis by making a model of a dummy track that can replicate Liwei's design for track junction. The main purpose of designing a dummy track is to simplify the design for the simulation, motion analysis already takes a couple of hours to run and if I add more complexity to the design the simulation run times would be even longer. **Figure 24** below shows the dummy track used for motion analysis. Notice how the top of the track, where the switch is engaged pulls inwards over the gap, this is to lift the bogie up on two wheels before it goes over the gap. This provides a smoother ride for the passengers inside the cabin. if we don't lift the bogie beforehand then we would have to have a slope on the track on the other end, which is where the 2 wheels of the bogie get back on the track. This is to avoid any collision of the wheels with the track and providing a smooth transition.

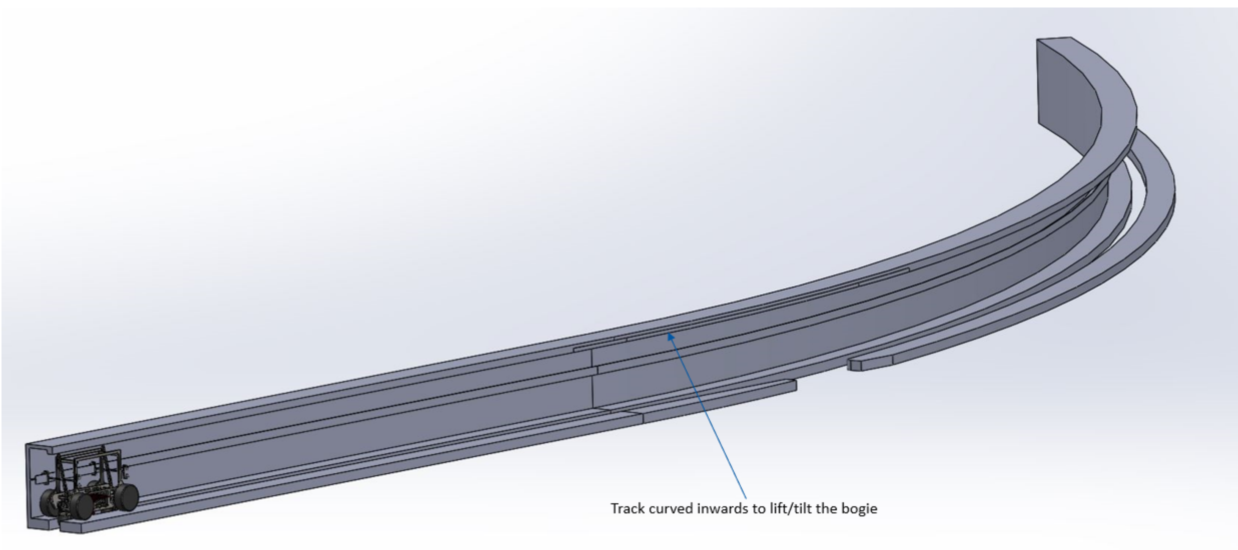

Figure 24:- Dummy track used for motion analysis simulations.

I had to set up the bogie assembly with each individual component on to this track. The problem with importing the whole bogie assembly into motion analysis is that if the components are not individually added Solidworks assumes them to be fixed considering the constraints of its parent assembly file. Once I had the assembly for the bogie and the track, I added mates to constrain the bogie on the track and deleted those mates before running the simulation. This is an important step; the bogie will not move if it is still constrained in any way to the track. The main reason why I had to constrain the bogie to the track is to place it at the correct starting position. I then set up the contacts between the track and the bogie. Solidworks is really good at recognizing the contacts and assigning the coefficient of static and kinetic friction for the contacts, I just had to specify the two materials that are coming in contact. To simulate a suspension system, Solidworks allows us to add springs and dampers as shown in **Figure 25**.

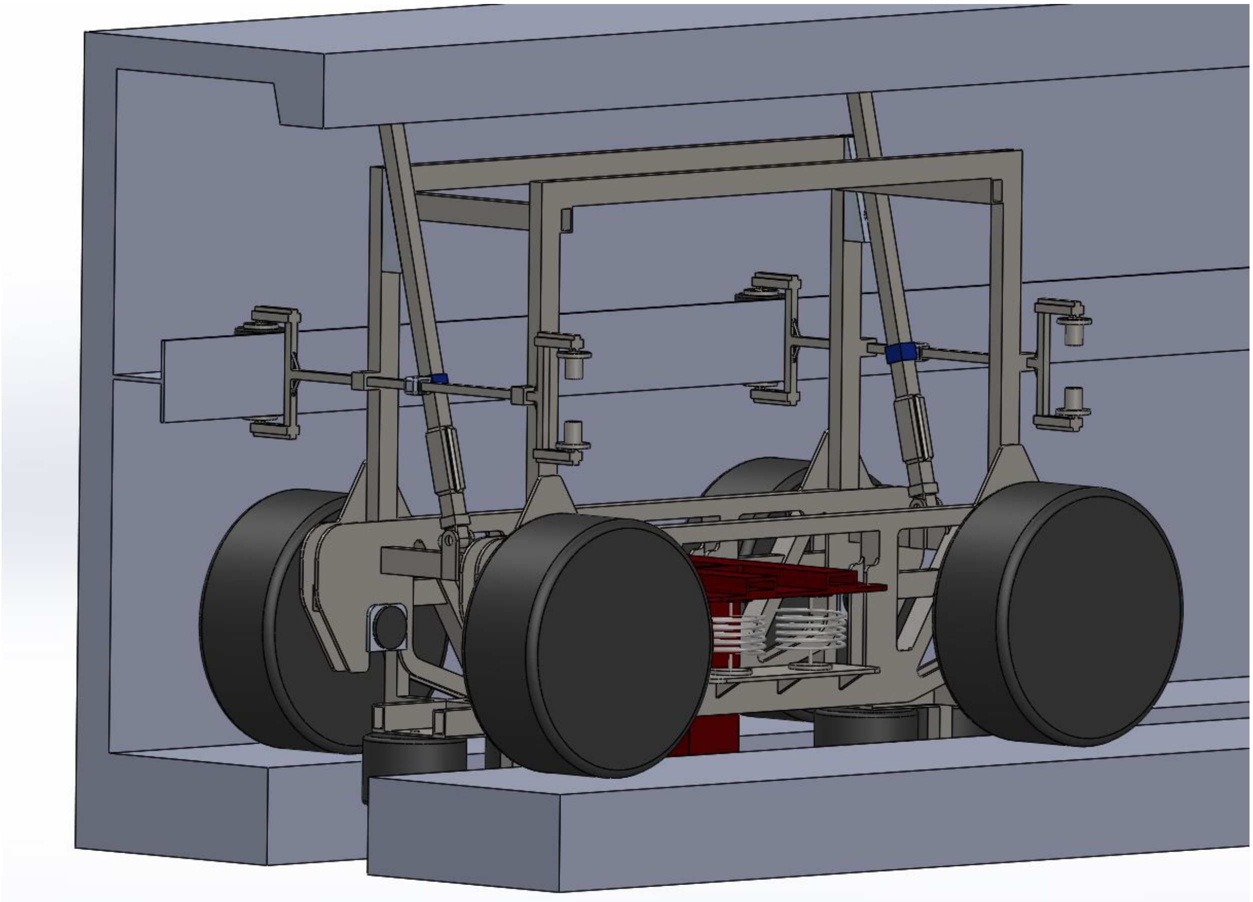

Figure 25: Bogie location on the dummy track along with suspension for motion analysis simulations.

I also added force on the frame base pointing downwards of 15000N, which is to simulate the weight of the battery pack and the cabin. I also activated gravity for this simulation so the bogie will take the force of its own weight and components like the switch mechanism. I then added 4 motors one for each wheel, since I plan on using hub motors to drive the bogie. I assigned 350RPM for each motor, with 14in wheels that is equivalent to 15mph. I tried using higher RPM, but the simulation would crash because of too many components moving too fast. To get results I set up some monitors, one for the vertical switch wheel, which will provide reaction force acting on the top wheel. The second monitor was on the slide switch wheel to see what the reaction force is acting on the side switch wheel.

6.2 Motion Analysis Results

Reaction forces acting on the vertical switch top wheel is shown in **Figure 26** below. I also showed the position of the bogie during the highest reaction force in each case. This helps with setting up static structural to check stresses, deformation, and factor of safety.

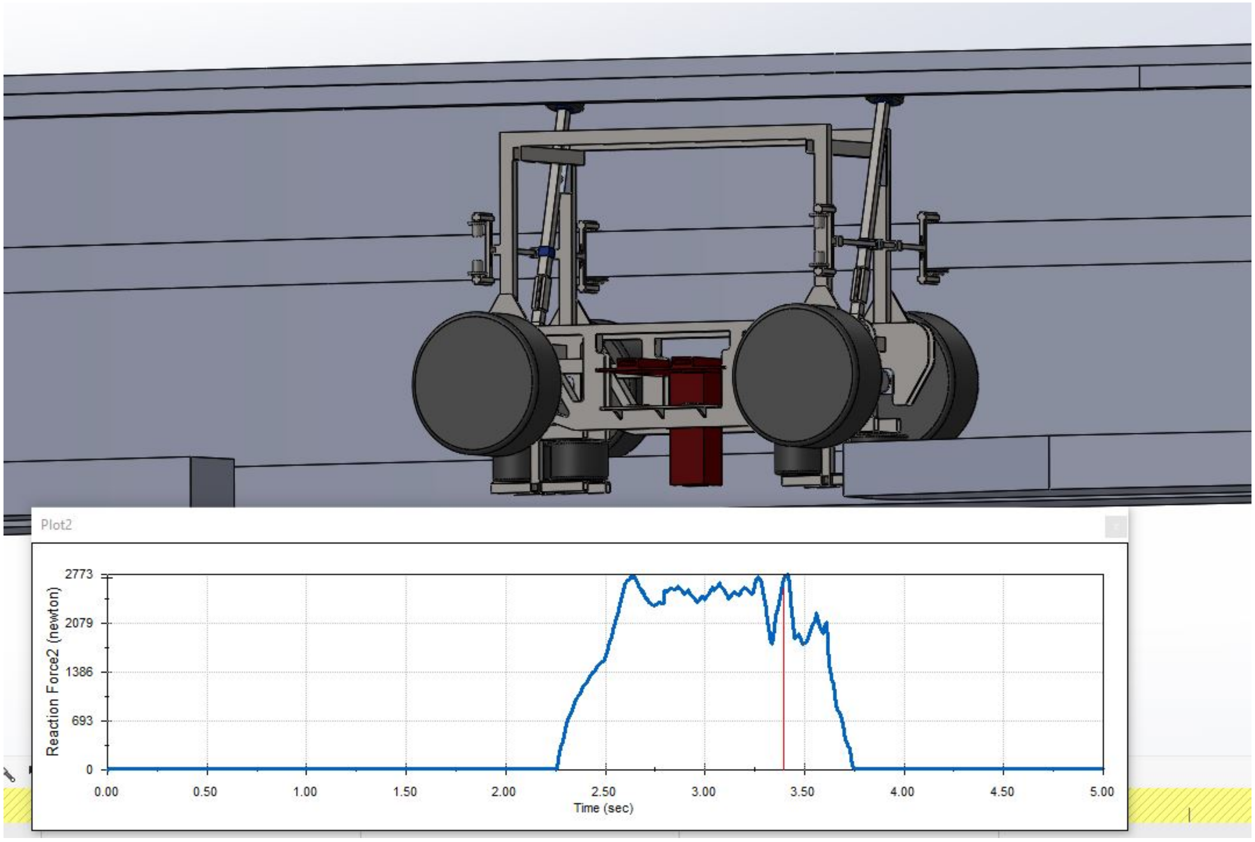

Figure 26:- Reaction force on top wheel Vs. Time plot along with the position of the bogie on the track during the highest force on the switch.

We can see that the highest force on the top switch wheel is 2773N when both wheels on one side of the bogie are over the gap. The vertical switch bar only takes load during junction and this plot shows exactly what was expected.

For the slide switch wheel reaction forces shown in **Figure 27**, we can see that the slide wheels do not take any loads during the junction, that is because the bogie is tilted preventing the wheels from touching the I-beam. These slide wheels are more of a fail-safe mechanism to prevent the bogie from derailing in case the top switch wheel fails.

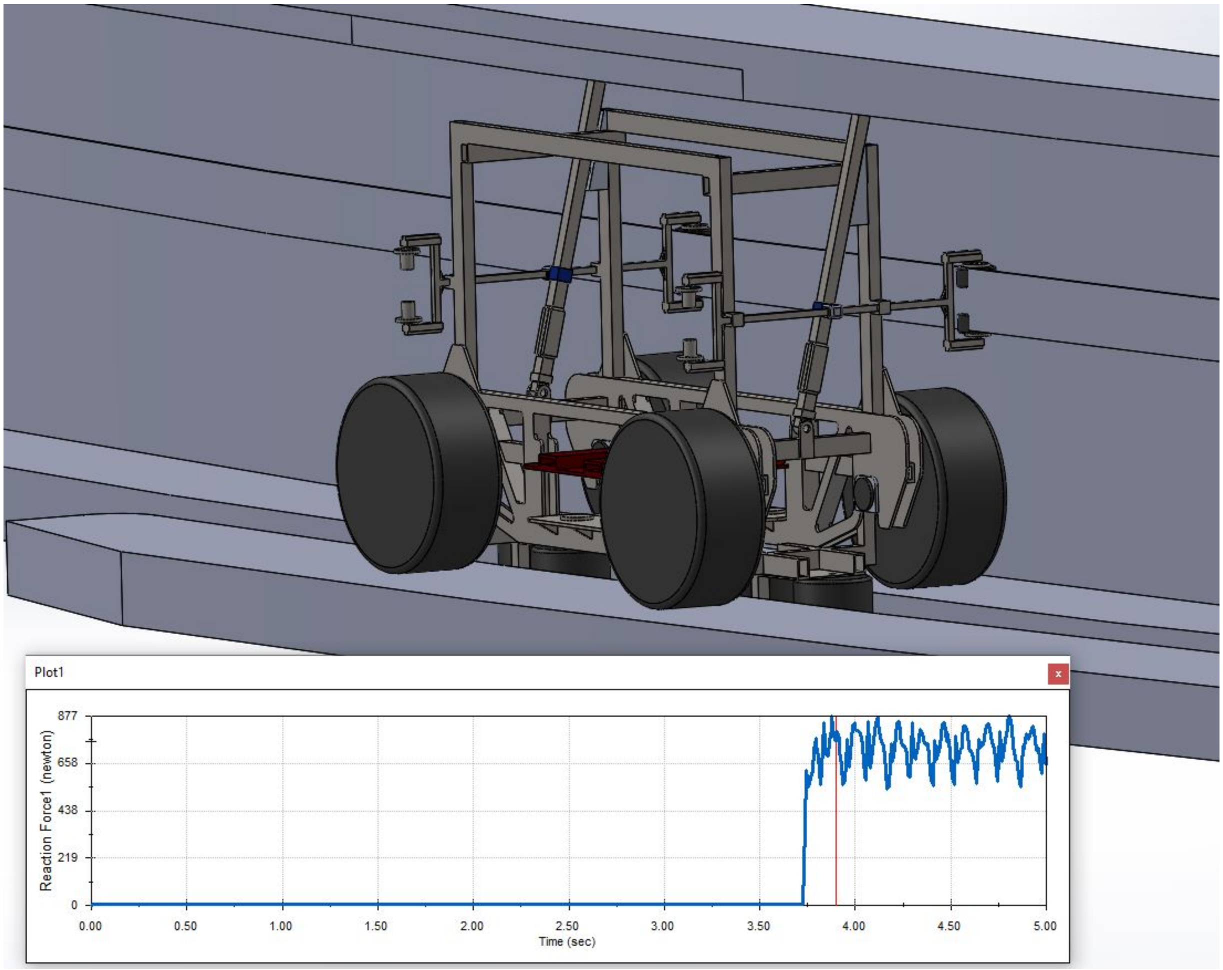

Figure 27:- Slide switch reaction force Vs. Time along with position of the bogie at the highest reaction force.

From the figure above we can see the highest force acting on the slide switch is 877N and it is during the curve section of the track after the junction. I expected the horizontal wheels at the bottom of the bogie to take the load during the curve section of the track. I had to set up a little bit of an offset between those wheels and the track for a smoother movement that is probably why we see the slide switch wheels taking the load.

I also used motion analysis to calculate the torque required to drive the bogie, **Figure 43** shows the plot of torque required Vs. time plot and the maximum torque for the drive wheel that stays on the track is 168N-m. I considered this while selecting a motor to drive this bogie. The motor selected to drive the bogie is shown in **Figure 44**. The selected motor provides a torque of 350N-m with a maximum current of 250A at 96V (QSMOTOR 12000W V4 E Car Hub Motor, n.d.). This motor is sufficient to run on flat tracks with a factor of safety of 2.0, but if we have ramps added to the track then we will need to upgrade the motor to 500N-m torque or above.

I used the same simulation to calculate the forces on the guide wheel at the bottom of the track. This is basically the forces acting on the guide wheel as it maneuvers the curve. This is important because there will some centripetal force acting on the bogie and since this wheel is to keep the bogie centered on the track it is countering that force. **Figure 28** shows the motion analysis result we can see the highest reaction force on the wheel highlighted in blue is 2276N.

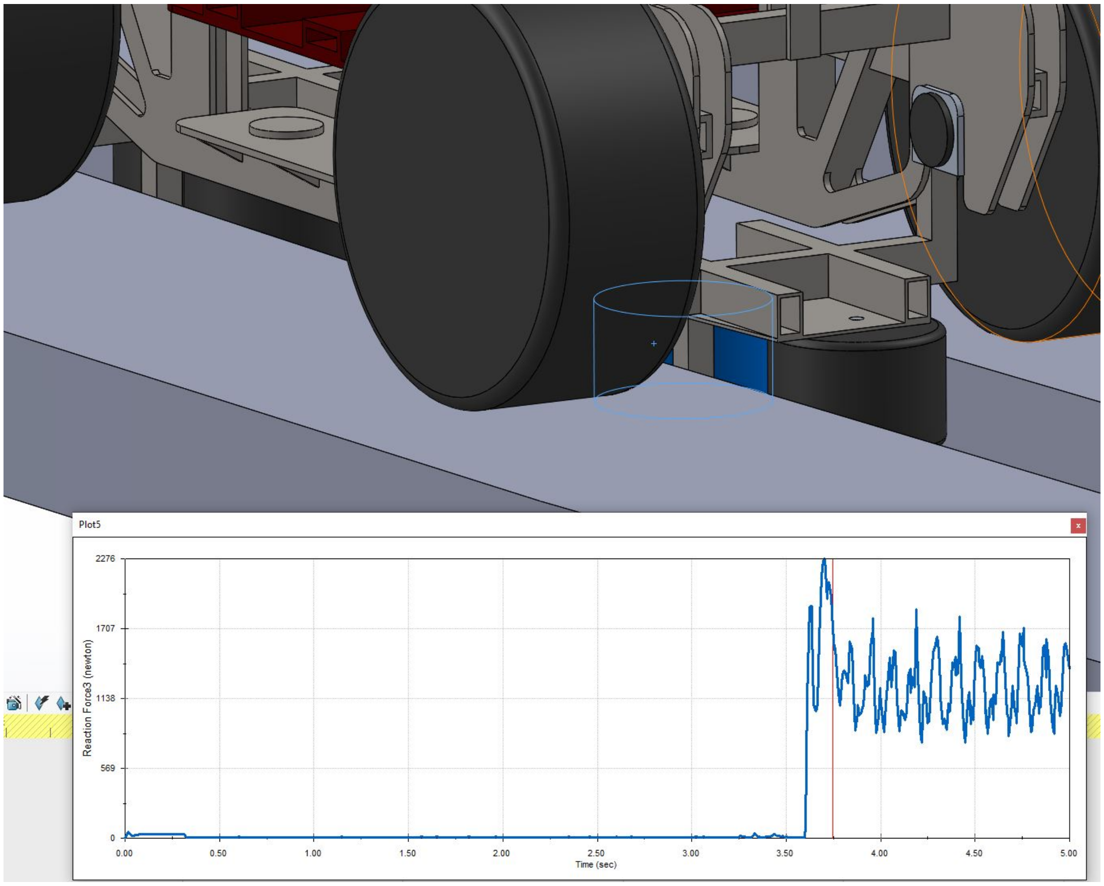

Figure 28:- Guide wheel reaction force Vs. Time plot.

To better account for centripetal acceleration I decided to run a motion analysis with lumped mass hanging from the bogie. This mass weights the same as we assumed the maximum cabin weight to be. This will account for centripetal forces acting on the lumped mass, this also accounts for the lever-arm from which the mass is hanging down. I then used the FEA option that is built into motion analysis to find out the stresses on the bogie base with a lumped mass cabin attached to it. We expect the highest centripetal load on the base when the bogie is going on a curved section. **Figure 29** shown below shows high stresses on one side of the frame base, this is due to the centripetal forces acting on the lumped mass. Since it was harder to replicate this in a static structural analysis, I had to settle with the FEA system that is built into the motion analysis. The problem with this system is it shows higher stresses compared to static structural and I am unable to control the mesh in motion analysis to try and get rid of any singularities. The stresses are on one side of the base as expected and from checking the deformation and factor of safety I get the highest deformation of 1.5mm at the bottom of the lumped mass and a factor of safety of 2.0.

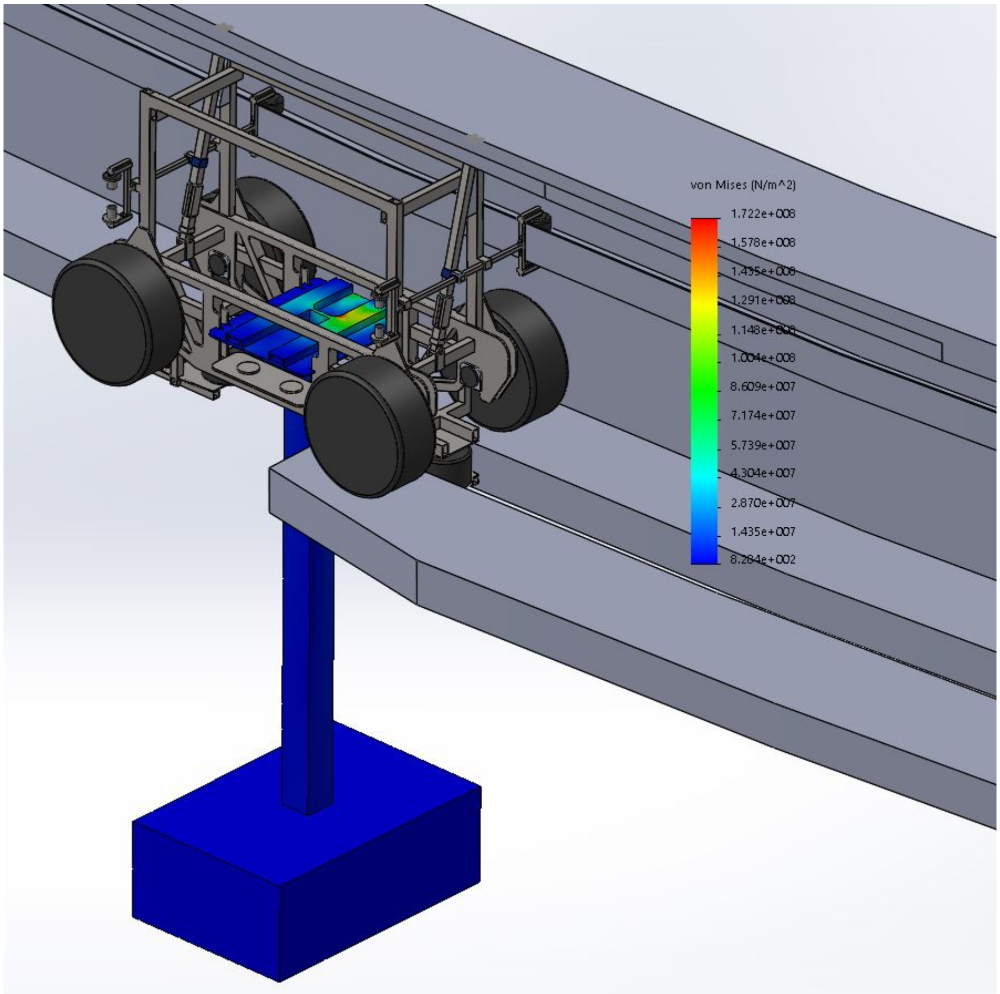

Figure 29:- Motion analysis FEA result showing Von-Mises stresses in bogie base due to centripetal forces.

7.0 FINITE ELEMNT ANALYSIS

All static FEA analysis for this project is done using SOLIDWORKS. I used the maximum amount of force from the motion analysis results to run static structural analysis for various components.

7.1 Frame

The frame is taking the load of the cabin and the battery pack. I determined the cabin weight to be 1000Kg and the battery pack weight is 100Kg, I am adding another 400Kg for any other components that are not put on the bogie yet, like controllers, sensors, and drivetrain. The maximum load the bogie wil1 be carrying is 1500Kg, which is 15000N, if we take gravity into account. For fixed support, I assumed that the placement of the wheels on the bogie is assumed to be fixed. Forces are represented with pink arrows and fixed support is represented with green arrows.

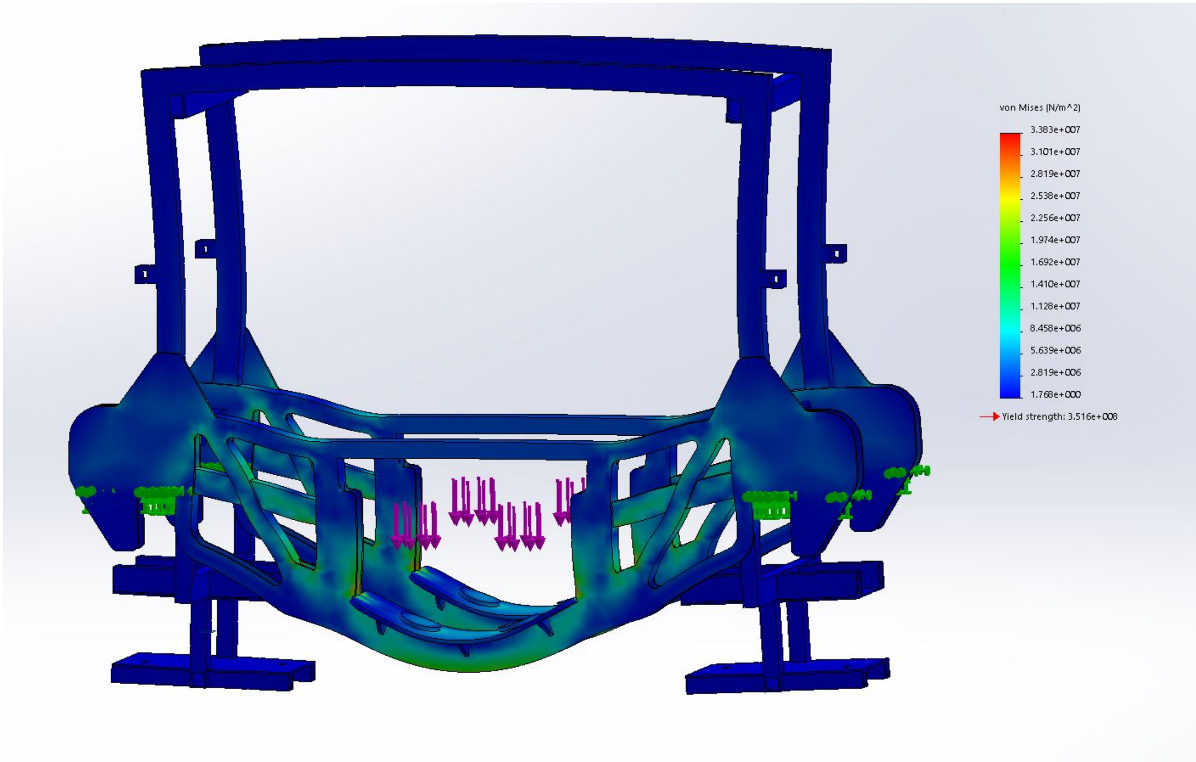

Figure 30:- Fringe plot showing stress in the bogie frame.

Figure 30 shows the stresses in the bogie frame due to the load of the cabin; we can see the highest stress is 3.4E7 N/m^2. **Figure 47** and **Figure 48** show the deformation and factor of safety respectively. The bogie frame deflects 7.8E-2mm with the factor of safety of 10.3.

7.2 Bogie Base

The bogie base connects the cabin to the bogie and will go under the same loading conditions as the frame. Since the base is attached to the suspension system, I am assuming that contact to be the fixed condition and adding 15000N of load at the bottom.

Figure 31 shows that the highest stress on the bogie base is 4.2E7 N/m^2 due to the load of the cabin and the battery pack. **Figure 49** and **Figure 50** show the deformation and factor of safety respectively. Under the maximum loading conditions, the bogie base deforms 4.8E-2mm with a minimum factor of safety of 8.4.

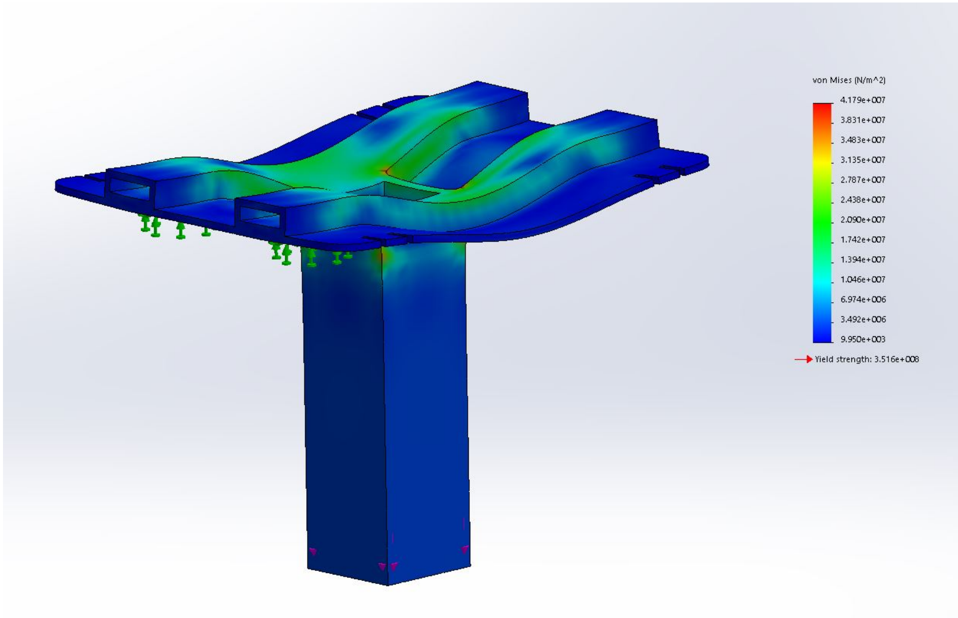

Figure 31:- Fringe plot showing stress in the bogie base

7.3 Vertical Switch

Vertical switch loading conditions are taken from the motion analysis results. From **Figure 26** we can see that the highest load acting on the vertical switch is 2773N pointing in the normal to the track surface, which is where the wheel is rolling on. For simplicity purposes, I am assuming that both vertical switches are under the same load of 2800N. Like the frame FEA analysis, I am assuming the place where the drive wheels are attached to be fixed.

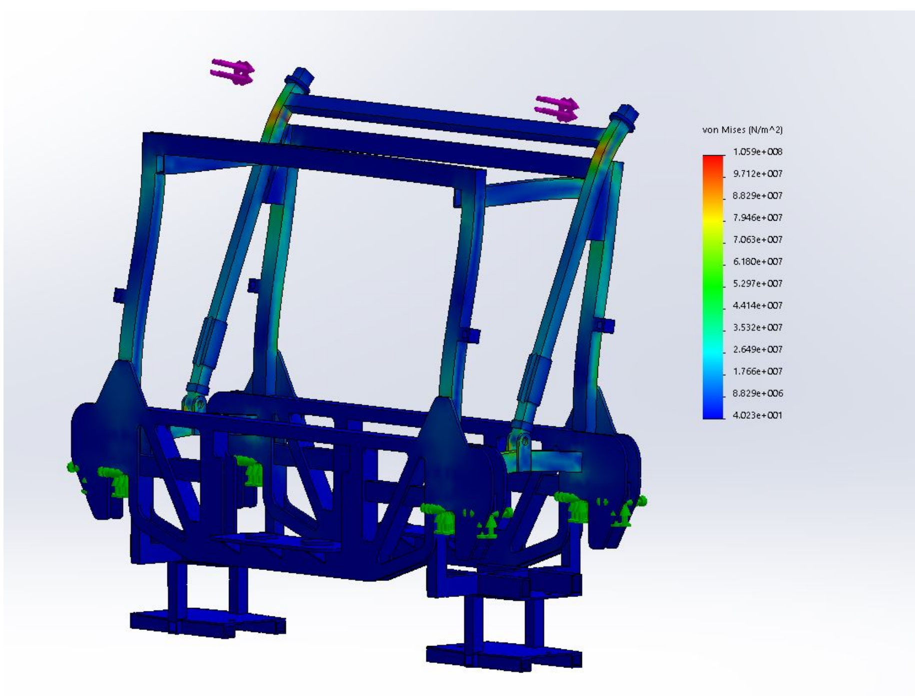

Figure 32:- Stress plot of frame and switch assembly under load as the bogie goes over the gap.

Figure 32 shows that the highest stress acting on this assembly is on the vertical switch bar with a magnitude of 1.05E8 N/m^2. We also see the maximum deformation on the vertical switch itself as shown in **Figure 51** with a magnitude of 0.9mm. For the factor of safety plots, I had to separate the two components into two separate plots, so it is easier to determine the minimum factor of safety for each component. **Figure 52** shows the factory of safety plot for the frame and **Figure 53** shows the factor of safety plot for the vertical switch. The minimum factor of safety of the frame is 3.6 and the minimum factor of safety of the vertical switch is 2.7.

7.4 Aluminum Support

As mentioned before the aluminum support block is mainly under compression between the vertical switch and the frame. I used the same loading condition as the vertical switch, which was 2800N. I added 2800N of force on the front side of the aluminum block with the rear side to be fixed as shown in **Figure 33**.

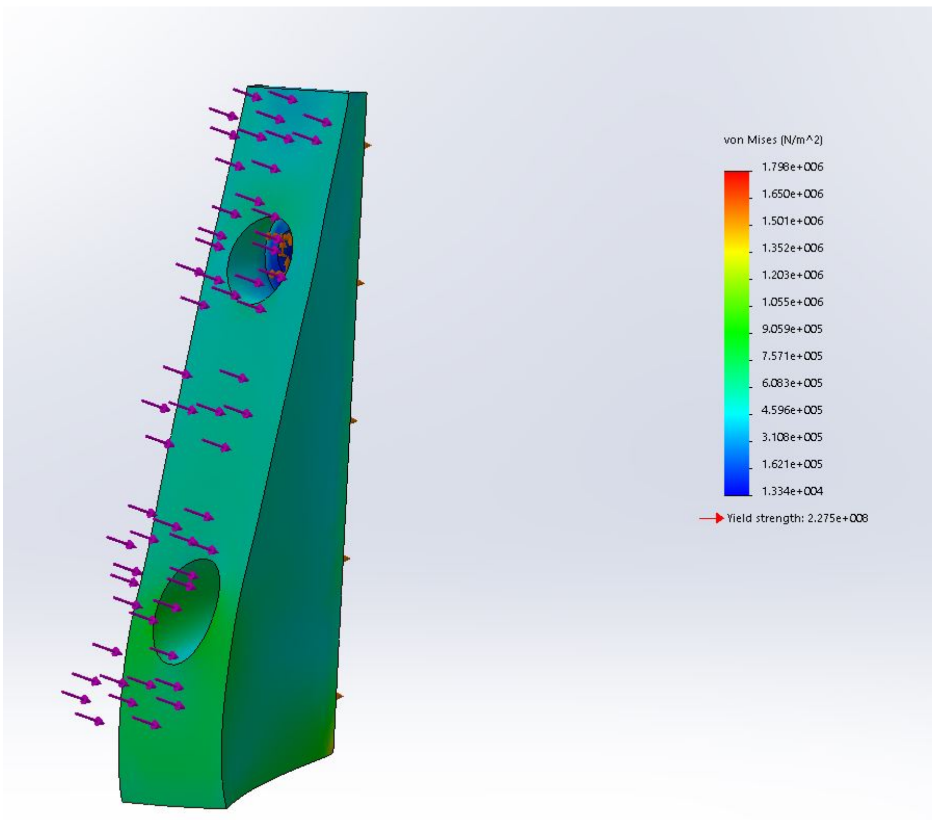

Figure 33:- Stress inside the aluminum support block as the bogie goes over the gap.

The maximum stress inside the aluminum support block as the bogie maneuvers the junction is 1.8E6 N/m^2. This was expected, since this is a very stiff component under compression, its main purpose is to transfer the load from the vertical switch bar to the frame. There is a very minor deformation of 8.6E-4mm with factor of safety of 126. This component can be changed to decrease the stiffness and to reduce the weight of the component. Since this part is already machined it would be easy to add couple more cuts to the program and lose some of the extra weight.

7.5 Sliding Switch

Sliding switch loading conditions are taken from the motion analysis results. From **Figure 27** we can see the maximum loading condition for the slider wheel is 877N. For structural analysis I am assuming the middle of the slider, which is connected to the vertical switch, is fixed. I am also assuming that there is no motion in Z direction, which is vertical from top to bottom of the bogie, and no motion in the Y direction, which is front to back of the bogie. To simulate this, I have added rollers to those surfaces as shown in figure below.

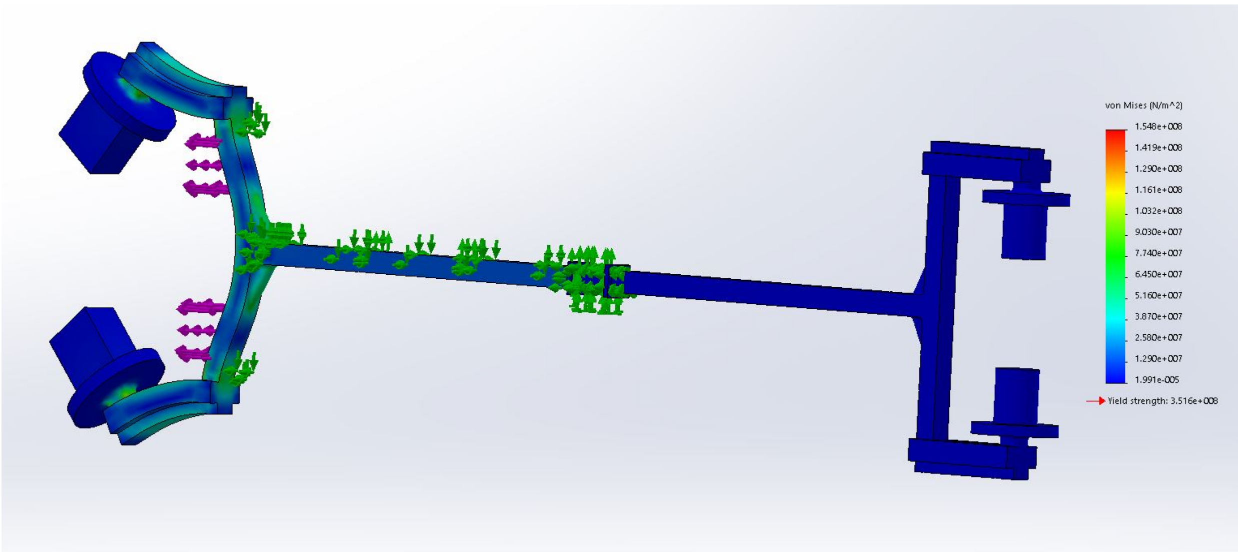

Figure 34:- Stress plot for the slider switch in maximum loading condition.

The highest stress on the slider switch is at the joints. I expected that, so I added a small rib with fillets to distribute the stress. Maximum stress is 1.54E8 N/m^2. **Figures 56** and **Figure 57** show the deformation and factor of safety for the slider switch respectively. The maximum deformation in the slider switch is 0.21mm, and minimum factor of safety of 2.27.

8.0 THERMAL ANALYSIS

For the water-cooled battery pack, I am using ANSYS Fluent to run a 2D CFD analysis to check the difference in temperature as the water flows through the channel. We expect the temperature in the battery cells to be higher closer to the outlet compared to the inlet because the water will absorb some heat from the cells as it flows through the channel. I will also run a steady state thermal analysis to check the temperature difference for the overall battery pack, which includes the ABS panels. I will run a transient thermal analysis to check how long it will take us to reach the steady state temperatures, this will help us get the time it takes to get the maximum temperature for the battery pack. We can then use the results for the transient thermal analysis to find the maximum thermal stresses and deformation in the battery pack.

8.1 Boundary Conditions, Assumptions & Material Properties

For boundary conditions I have internal heat generation of the cells to be 6.2E4$\mathrm{W/m^3}$. I am using forced convection with inlet temperature as 22ºC ≈ 295 Kelvin. I am assuming the battery pack is enclosed and therefore, there is no direct convection from the outside air. The inlet velocity for water is assumed to be 0.3m/s.

Table 1:- Material properties used for thermal analysis.

No.	Component	Material	Youngs Modulus (MPa)	Poisson's Ratio	Density (Kg/m^3)	Coefficient Of thermal Exp. (K^{-1})	Thermal Conductivity (W/m-K)	Specific Heat (J/Kg-K)
1	Battery Panels	ABS	2620	0.35	1100	0.00012	0.1	1600
2	Water Channels	AL-6061	7E4	0.33	2700	2.34E-5	167	896
3	2170 Cell	-	1200	0.08	2548.2	1.2E-5	68	830
4	Thermal Pad	-	6.89	0.47	2540	0.00071	6	370

Table 1 shows all the material properties used for various thermal analysis. For 2D CFD I modeled one water channel with one inlet and one outlet, and I am assuming the rest of the channels have same temperature and velocity contour.

8.2 2D CFD Analysis Using Water as Coolant

The 2D CFD analysis is done using ANSYS Fluent. Water enters the channel with inlet velocity of 0.3m/s at 295K. The battery cells are assigned internal heat generation, so they are at a higher temperature compared to water, as the water flows it takes away some of the heat.

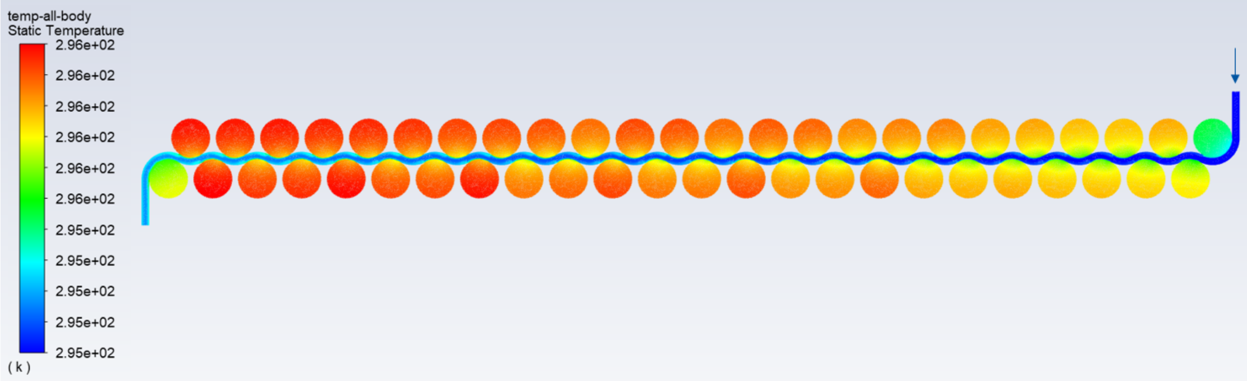

Figure 35:- Temperature contour of one water channel using water as coolant.

From the figure above we can see that the cells near the inlet, which is to the right, are at a lower temperature compared to the ones closer to the outlet. That is because the water heats up as it flows through the channel. The goal is to keep all the battery cells at even temperature, and in this case, we can see that the cells are still within 1 Kelvin. The velocity contour shown in **Figure 58** shows that the velocity in the center of the channel is much higher, that is because of the boundary layer. The water near the walls gets stuck to the walls and therefore have 0m/s velocity and since there is a constant inlet velocity the fluid flows faster at the center of the channel.

8.3 2D CFD Analysis Using Water & Glycol Mixture

I also decided to try the same simulation with same boundary conditions, but with different coolant. In this case I am using water-glycol mixture as coolant, this will prevent the water from freezing during colder days.

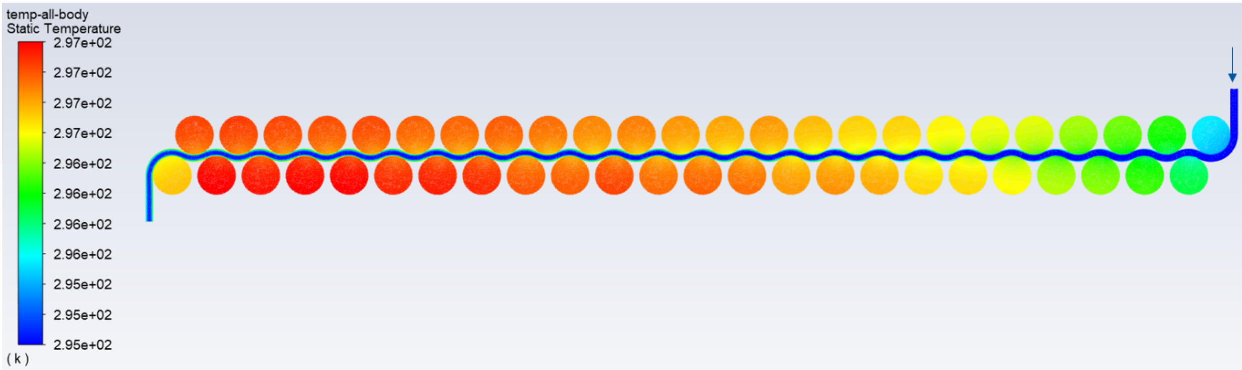

Figure 36:- Temperature contour of one water channel using water-glycol mixture as coolant

Figure 36 shows the temperature contour of the water channel and the cells and we can see that this time there is a 2 Kelvin temperature difference between the ambient temperature and the hottest cell temperature. The velocity contour shown in **Figure 59** also shows much higher difference in the velocity from the side of the walls to the center of the channel. Since water-glycol mixture is more viscus compared to just water we get overall slower velocity in the channels with larger boundary layers.

8.4 Static Thermal Analysis

To run static thermal analysis, I had to simplify the geometry, since it is a 3D analysis and there are more than three hundred cells in the battery pack it would take days for the simulation to finish. Since there are three modules in the battery pack, I am only considering one module for this analysis and will assume the others have the same thermal loads. Even with this simplification, there are still more than a hundred cells, which will result in long simulation times. Since I have two inlets and two outlets, I decided to take advantage of the symmetry plane in the middle of the battery pack. By taking symmetry into consideration I am left with half of the battery pack. I am still using the same internal heat generation for the cells and for the water channels I am adding convection at 22ºC.

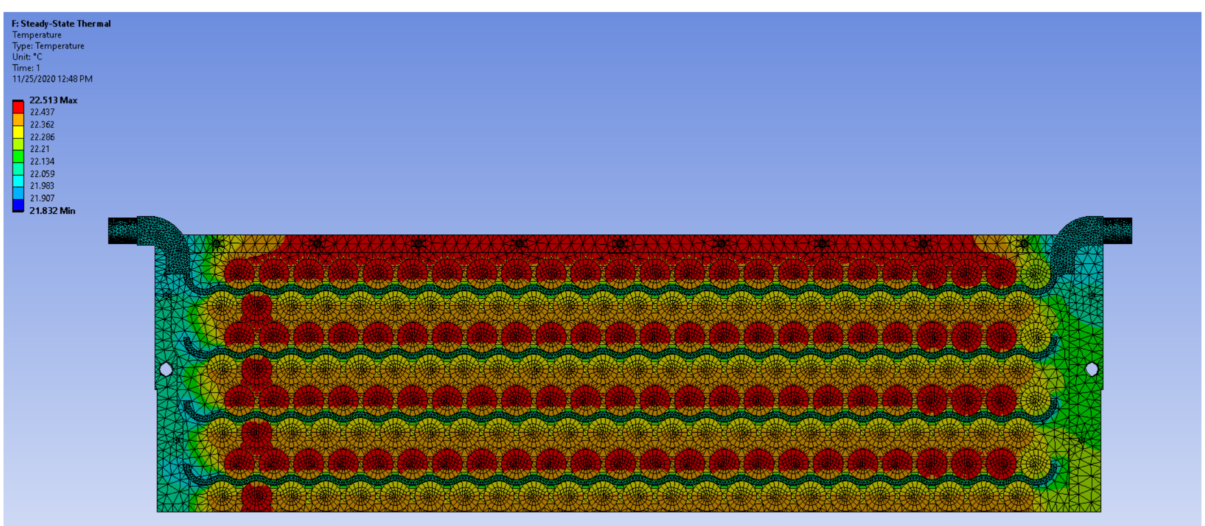

Figure 37:- Temperature plot for 2170 water-cooled battery pack.

Figure 37 is the top view of the battery pack, and we can see that the temperature is still within 1ºC from the ambient temperature. We can also see that the ABS plate on the side of the pack is at a higher temperature. That is because this is a steady-state analysis and it assumes a long amount of time has passed until that temperature is stable, and since ABS is basically an insulator it will take a lot longer for heat to transfer on to that ABS side plate.

8.5 Transient Thermal Analysis

Transient thermal analysis is used to find out how long it takes for a system to reach steady state temperature. I ran the transient thermal analysis for 240 seconds to make sure I can get close to steady state temperature within that time period. Maximum temperature from the steady state analysis is 22.51ºC. From **Figure 38** we can see that it takes 120 seconds to reach steady state temperature.

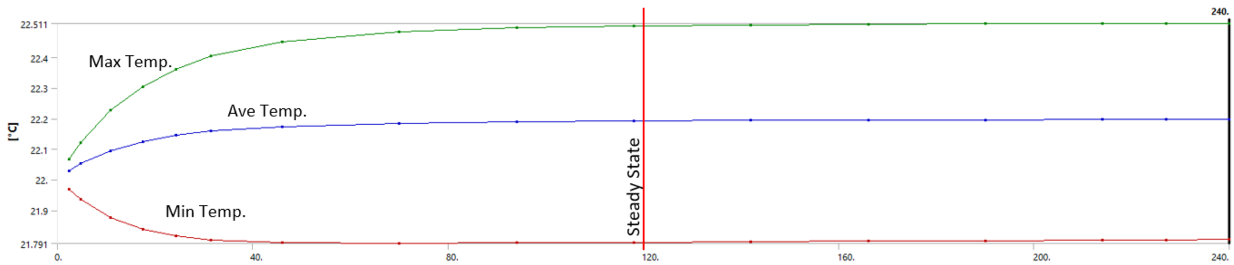

Figure 38:- Transient analysis results showing Maximum temperature Vs. Time.

8.6 Static Structural Analysis Under Thermal Load

I used the results from the transient thermal as thermal loads for static structural analysis. For fixed geometry I am assuming that all the bolts that hold the battery pack together are fixed. With the thermal load we expect the materials to expand and have internal stresses, especially near the connections.

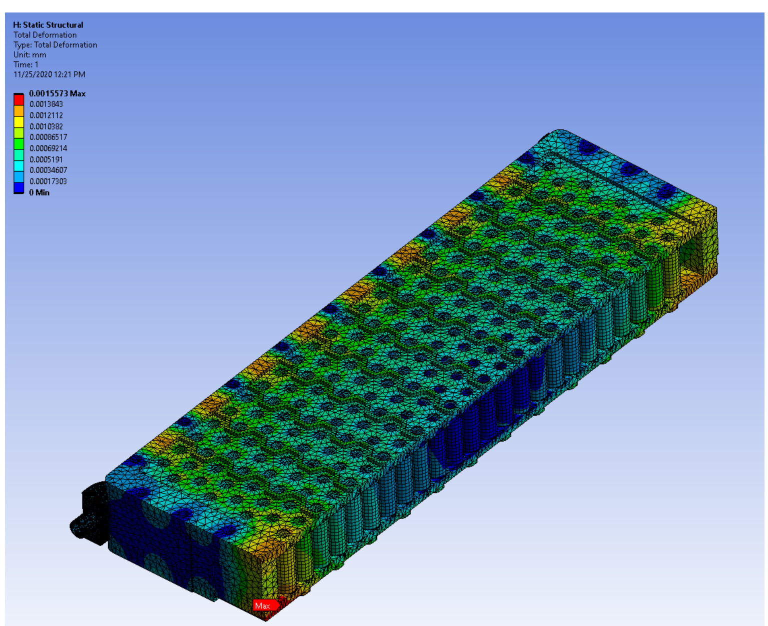

Figure 39:- Deformation plot of the water-cooled battery pack under thermal load.

We can see that the ABS plates on the top and bottom of the battery pack deform mostly closer to the edges, that is because the middle of the battery pack is cooled with water channels. The highest deformation we see is 0.0015mm. I also did stress analysis with the thermal loads from the transient thermal analysis. I expect the cells to expand and the ABS plats that are holding the cells to have high stresses.

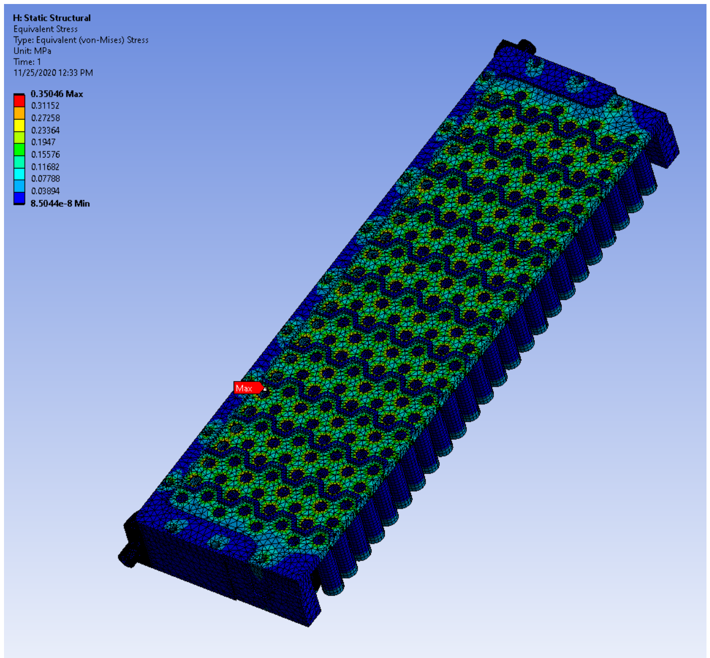

Figure 40:- Stress plot of the water-cooled battery pack under thermal load.

As expected, the highest stress is in the ABS plate where the cells are attached. The maximum stress due to thermal load is 0.35MPa. To get the factor of safety for the ABS plates I used the yield strength for ABS plastic.

$$F.O.S = \frac{Yield\ Strength}{Stress} \qquad (2)$$

Using **Equation 2** the factor of safety for ABS plates is 11.4.

8.7 2D CFD analysis for air cooled battery pack.

I also decided to run a 2D CFD analysis of the battery pack with air cooled system. In this case I am considering the whole battery pack, which is all three modules stacked as shown in **Figure 21**. Boundary conditions for air-cooled 2D CFD are shown in **Figure 41**. We can see that inlet for air is at the bottom and outlet at the top with ABS plates and battery cells on the sides. I am using same internal heat generation as water-cooled 2D CFD analysis. I am using same inlet velocity as water in the water-cooled battery pack CFD analysis. Inlet velocity is 0.3m/s at 295 Kelvin.

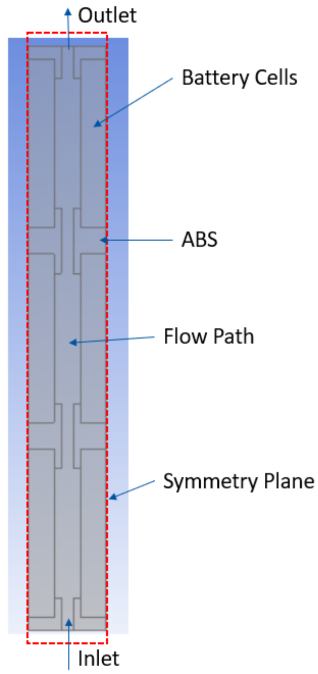

Figure 41: Air-cooled battery pack boundary conditions.

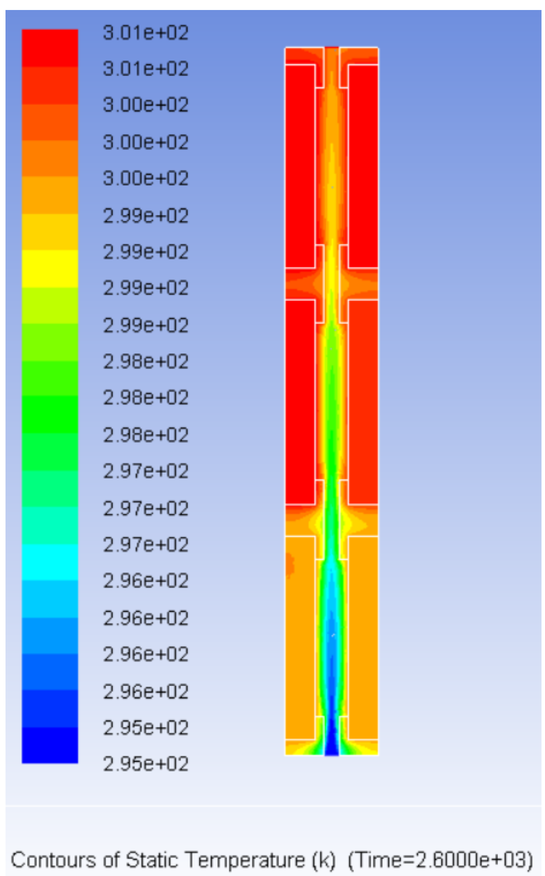

Figure 42: Temperature contour of air-cooled 2D CFD analysis

From **Figure 42** shown above, we can see that we get higher temperatures when compared to water-cooled 2D CFD analysis. The air-cooled analysis shows more than a 6-degree difference compared to the ambient temperature of 295 Kelvin. These results are highly dependent on the inlet area, in this case, I have an inlet diameter of 5mm. I have also tried to run this simulation with a smaller inlet diameter of 2mm, and results for that are shown in **Figure 59**. As I decrease the inlet diameter more and more air is trapped inside the pack and the temperature goes up. Another downside about the air-cooled battery pack is that if this is not a closed system and we are using ambient air from outside and pushing it into the pack, we might wet debris along with it. We could add a filter in the front but that only restricts the flow of air.

9.0 DISCUSSION

The main components for this project are the frame of the bogie, the switching mechanism, and the battery pack. I ran motion analysis to simulate maximum loading conditions for the frame and the switch mechanism, to make sure they all had a factor of safety of 2.0 or above. I used the maximum load of 15000N, which includes the weight of the cabin, the battery pack, and some extra wiggle room in case we add more components to the bogie. Under these maximum loading conditions, the factor of safety for the bogie frame is 10.3. Similarly, for the vertical switch, I ran motion analysis with the maximum load on the bogie and monitored the maximum load on the top wheel. Using that maximum loading condition for the vertical switch I get a factor of safety of 2.7, which is lower than I expected, we can increase the stiffness of the vertical switch by adding ribs or just using thicker tubes. For the aluminum support block, I get a factor of safety of 126, which is much higher than what I expected. Since this part is machined it would be easy to add a couple more cuts to reduce the weight of the component and reduce the stiffness. For the slider switch, the maximum load was during the turn on the junction with 877N force. Using that force and running a static structural analysis I get a factor of safety of 2.27, which is lower than expected but still above 2.00.

The battery pack is designed to power this bogie it has a capacity of 21.8kWh. In order to make sure that the cells don't overheat or lose their capacity too quickly, I introduced active cooling to the pack. Active water-cooling using water channels keeps the batteries within 1ºC from the ambient temperature and keeps all the batteries at close to the same temperature. I also considered the thermal expansion of the batteries and made sure the ABS side panels that hold the batteries are not under too much stress. With the maximum stress from the thermal loads, I get a factor of safety of 11.4 for the ABS plates.

10.0 CONCLUSION AND FUTURE WORK

I have finished most of the design work for this project, starting with the switching mechanism, battery packs, suspension system, and bogie frame. However, there are still some important details missing. We need a battery management system to properly control the voltages and current of the battery pack and more importantly to charge the battery pack. There are also different other methods of cooling the batteries so we can try to air-cool the batteries by pushing air into an enclosed battery pack. There are also other configurations of the water channels instead of having them set up vertically we can try setting the channels horizontally and check the temperature difference. We also need enclosures for the BMS system and for motor controllers. Typically, these chips need to be water-cooled or air-cooled with a heatsink. I have designed multiple enclosures for BMS and controllers for Lightning Motorcycle, so as soon as we agree on the boards it will be very easy for me to design enclosures and find a place for them on the bogie.

We need four hub motors to drive the bogie, I selected a 350N-m torque hub motor for my bogie, but this does not meet the factor of safety of 2.0 if we add ramps to the track. we need hub motors with 500Nm or above torque. We also need to program the active suspension to keep the cabin straight as the bogie tilts at the junction. Therefore, we need to make sure it changes stiffness depending on the weight inside the cabin. Another important thing to consider for the bogie is crosswinds. We need to make sure that the crosswinds do not create too many problems for our bogie. The important thing to note is that cabin is hanging on an active suspension system, which can compensate for reducing the amount of load from the cabin to the bogie due to crosswinds. For the slider switch, we need to account for any broken bearings or drag on one of the wheels, this will result in a torsional force. I did use square tubes so it will help with the torsional force.

This bogie is designed to be a prototype, there are multiple parts machined and welded together to form the frame of the bogie, in the long run however we would want this bogie to be casted in a maximum of two to three parts. Tesla recently introduced one-piece casting for their Model Y (Lambert, 2020). This casting used to be 60 different parts welded together but now it’s just one piece cast in one go, this reduces the cost and manufacturing time and increases production speed.

11.0 REFERENCES

Acoba, M. (2016, May 25). A Solar Powered Automated Public Transportation System. Retrieved from https://www.inist.org/library/2016-05-25.Alvarez (ed).Spartan Superway Spring 2016 Report.SJSU ME 195B.pdf

Albright, G. (2018). Thermal Management of Lithium-ion Batteries. Retrieved 21, 2020, from https://www.psma.com/sites/default/files/uploads/tech-forums-transportation-power-electronics/presentations/is125-thermal-management-lithium-ion-batteries.pdf

Benjamin, J. (2019, September 30). Request For Information 2019-DOT-PPD-4 New Transit Options: Airport-Diridon-Stevens Creek Transit Connection. Retrieved May 9, 2020, from https://www.sanjoseca.gov/home/showdocument?id=45799

Bower, G. (2019, April 24). Tesla Model 3 Battery Cooling Much-Improved ... Track Mode? Retrieved from https://insideevs.com/news/338711/tesla-model-3-battery-cooling-much-improved-track-mode/

Cabintaxi PRT System. (2012, September 20). Retrieved February 8, 2020, from http://faculty.washington.edu/jbs/itrans/cabin.htm

Coaquira, D. (2019, May 19). Powertrain and Wayside Integration into SPARTAN Superway Utilizing Current Collector Mechanisms and Supercapacitor-Only Energy Storage for ATN Vehicle Applications. Retrieved from https://www.inist.org/library/2019-05-19_Full-Scale_Wayside_Power_FinalReport.SpartanSuperway.pdf

Furman, B. J. (2016, July). The Spartan Superway: A Solar-Powered Automated Transportation Network. Retrieved May 9, 2020, from https://www.inist.org/library/2016-07.Furman.Spartan Superway - A Solar Powered Automated Transportation Network.ASES Solar 2016.pdf

Furman, B., & Swenson, R. (2019, October 14). Solar Powered Automated Rapid Transit Ascendant Networks. Retrieved from https://www.inist.org/library/2019-10-14.FurmanSwenson.SPARTAN.SJSU_WhitePaper.pdf

Gustafsson, Bengt. (2014). *U.S. Patent No. 008807043B2*. Washington, DC: U.S. Patent and Trademark Office.

Hagstrom, Eric, et al. (2017). Spartan Superway Development a White Paper. Retrieved from https://www.inist.org/library/2017-03-14.FurmanSwensonHagstrom.SpartanSuperwayWhitePaper(A4).SpartanSuperway.pdf.

Irving, J. H. (1978). Fundamentals of personal rapid transit based on a program of research, 1968-1976, at the aerospace corporation, El Segundo, California. Lexington (Mass.): Lexington Books.

Lambert, F. (2020, August 16). Tesla is installing world's biggest casting machine outside Fremont factory. https://electrek.co/2020/08/15/tesla-world-biggest-casting-machine-outside-fremont-factory/.

Lu, L. (2020, May). SPARTAN Superway: Guideway Design and Fabrication Method. Retrieved April 15, 2020, from www.inist.org/library/

Loukaitou-Sideris, A., Peters, D., & Wei, W. (2015). Promoting Intermodal Connectivity at California's High Speed Rail Stations.

Lyons, K. (2020, September 23). Here are Tesla's biggest announcements from Battery Day. The Verge. https://www.theverge.com/2020/9/22/21450840/tesla-battery-day-production-elon-musk-tabless-range-cathode-cobalt-plaid.

McMasterCarr. (n.d.). Retrieved December 06, 2020, from https://www.mcmaster.com/90186A108/

Niles, J. (2019). Automated Vehicles Have Arrived: What's a Transit Agency to Do?.

Norman Y. Mineta International Institute for Surface Transportation Policy Studies. (1999). Driving into the twenty-first century: technology solutions to transportation problems symposium, November 16, 1998. San Jose, CA.

QSMOTOR 12000W V4 E Car Hub Motor: Motors: - AliExpress. aliexpress.com. (n.d.). https://www.aliexpress.com/item/4000976129591.html?spm=a2g0o.detail.0.0.384257e5ifFWN7.

Siemens H-Bahn - Switching. (n.d.). Retrieved from http://www.monorails.org/tMspages/TPSiemsw.html

The Futran System. (n.d.). The future of transportation is now the present. Retrieved from https://futrangroup.com/

U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved from http://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php.

Wills, John B., "Government Clean Air Regulations and Tesla Motors" (2014). *Master's Projects*. 372.

Zhang, X., Yang, B., Zhang, M., & Hu, S. (2017). The Analysis of the Stiffness-Damping Parameters of a H-Bahn Vehicle. SAE Technical Paper Series. doi: 10.4271/2017-01-1890

12.0 APPENDIX

Figure 43:- Screw-to-install rivet nuts (McMasterCarr, n.d.)

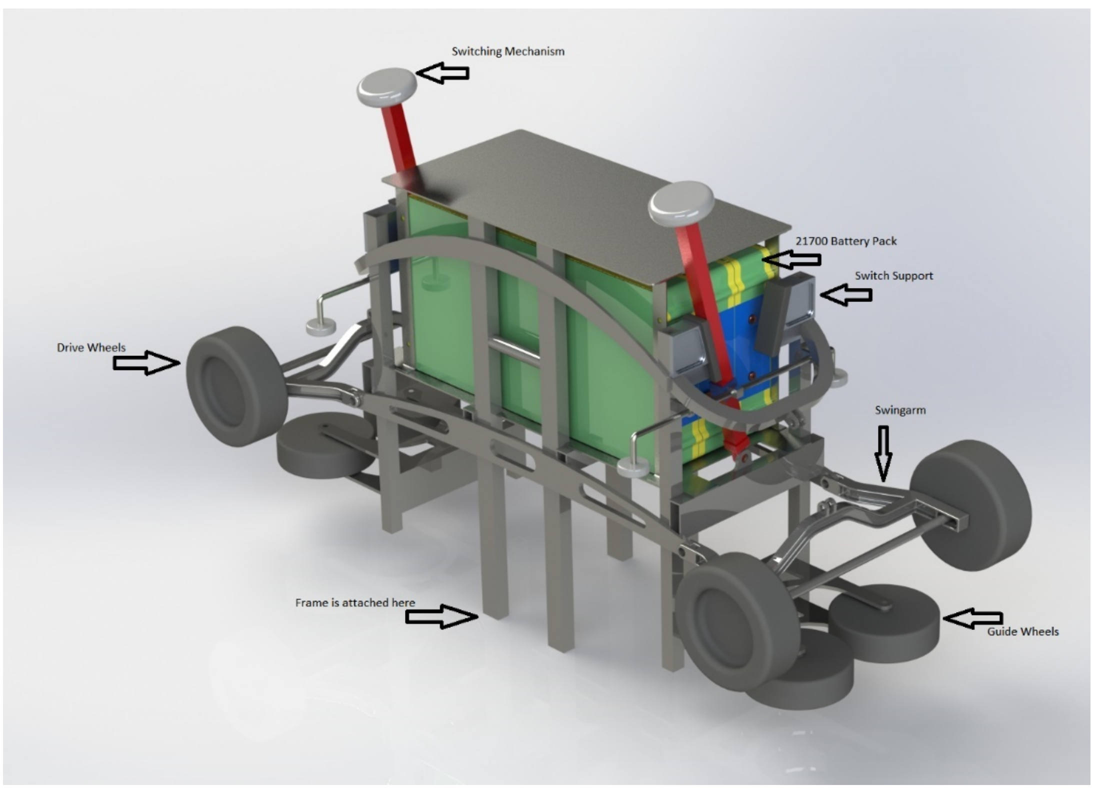

Figure 44:- Bogie assembly as of May 5th, 2020.

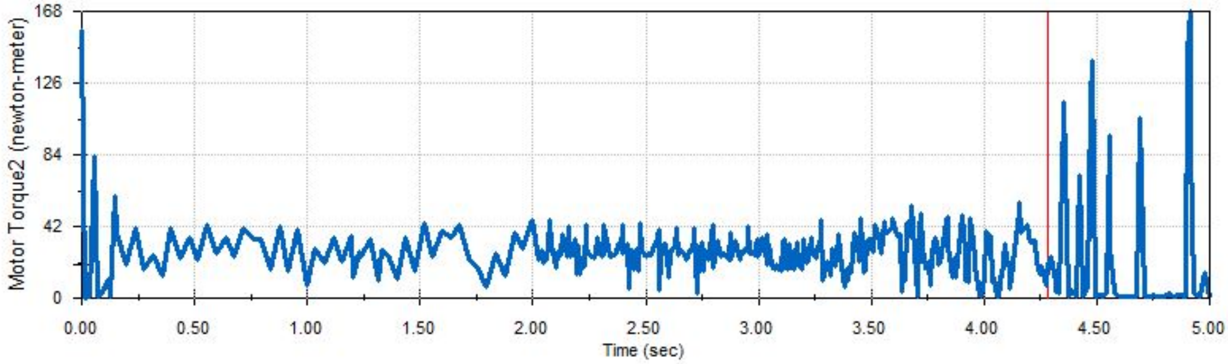

Figure 45:- Motor torque required to drive the bogie Vs. Time plot from motion analysis

Figure 46:- Motor selected to drive the bogie (QSMOTOR 12000W V4 E Car Hub Motor, n.d.).

12.1 FEA Results

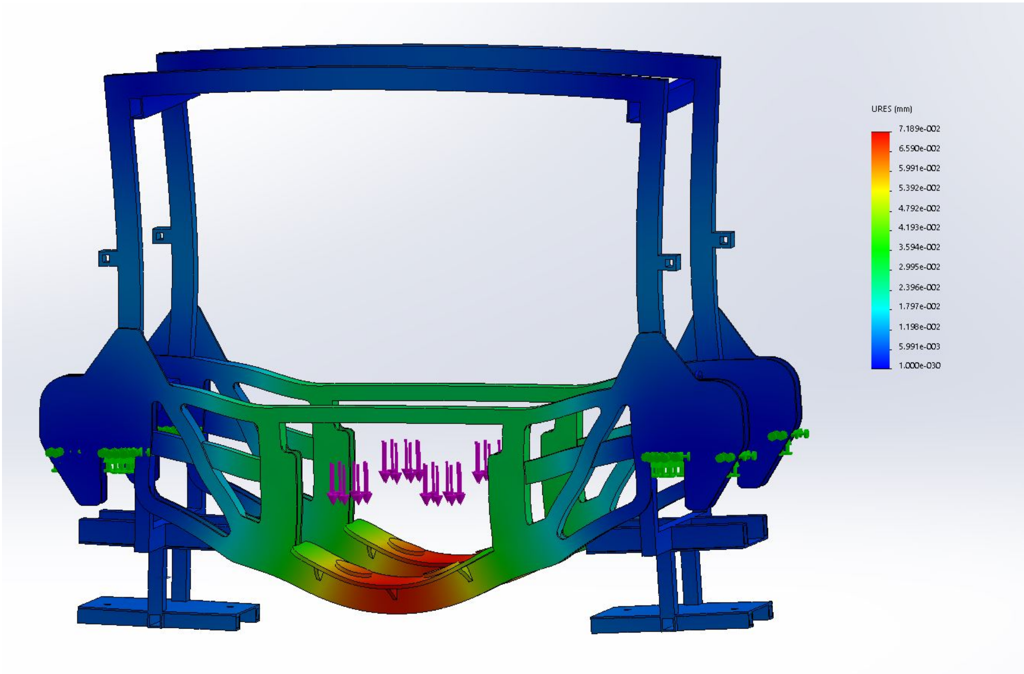

Figure 47:- Deformation fringe plot of the bogie frame under max load of the cabin.

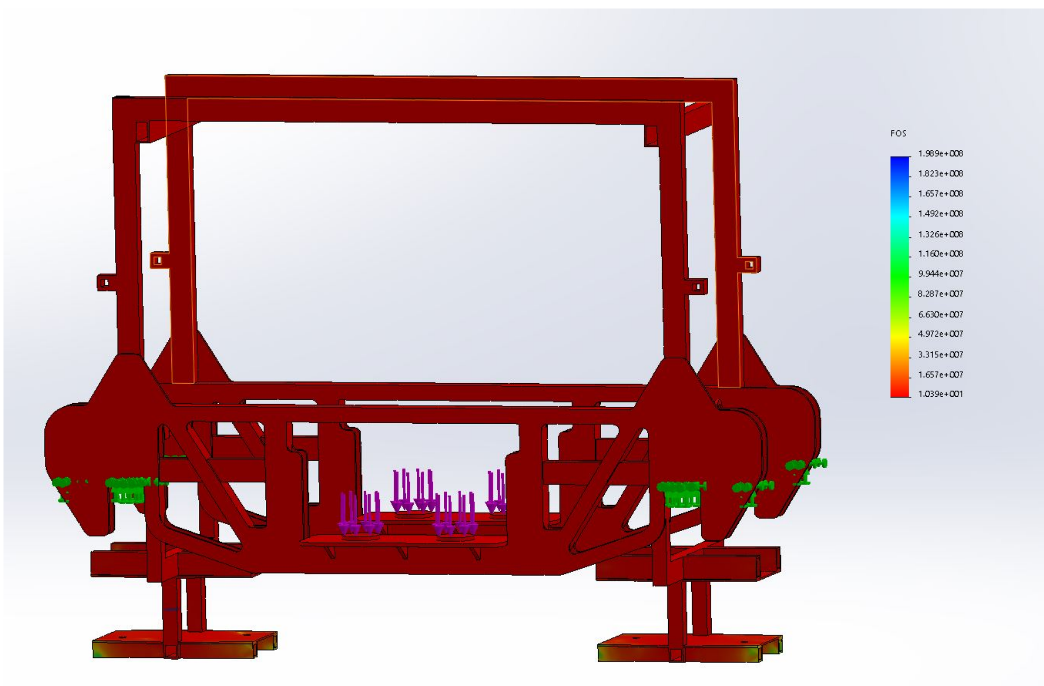

Figure 48:- Factor of safety fringe plot of bogie frame under load.

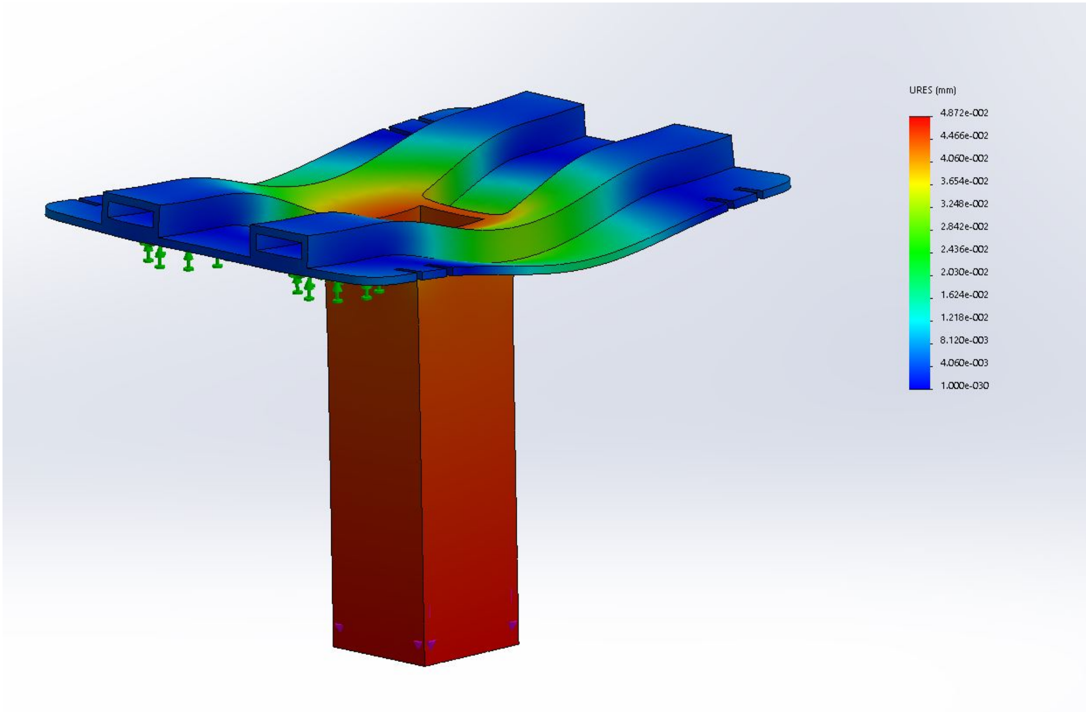

Figure 49:- Deformation fringe plot of the bogie base under max load of the cabin.

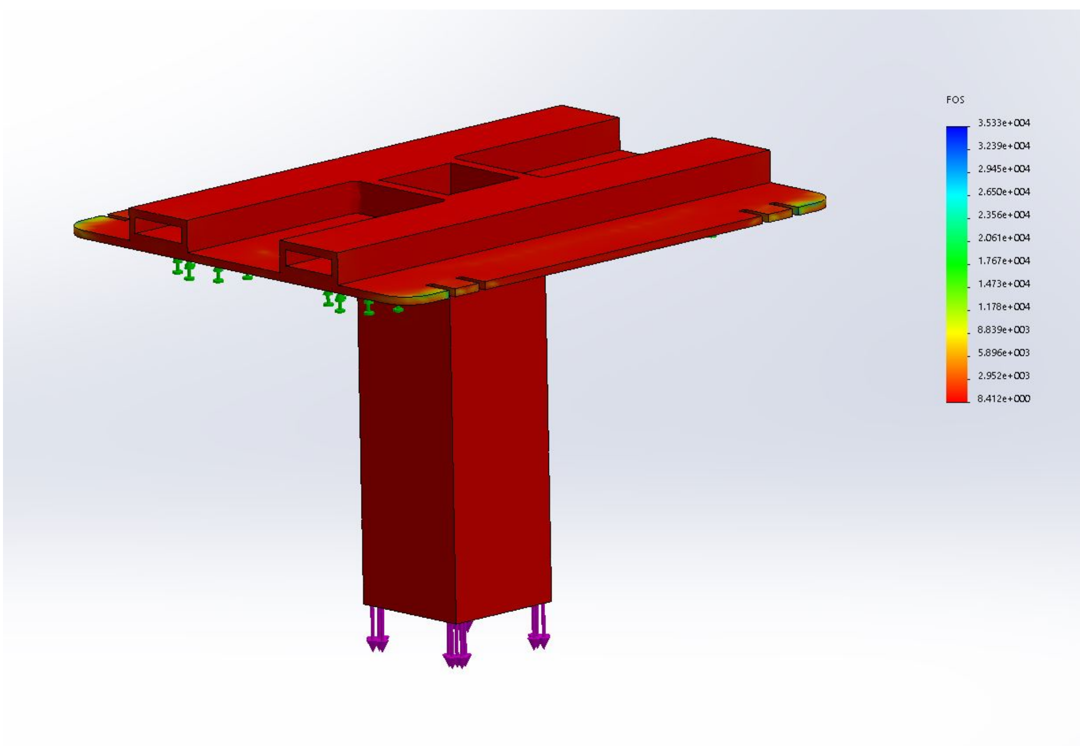

Figure 50:- Factor of safety fringe plot of bogie base under load

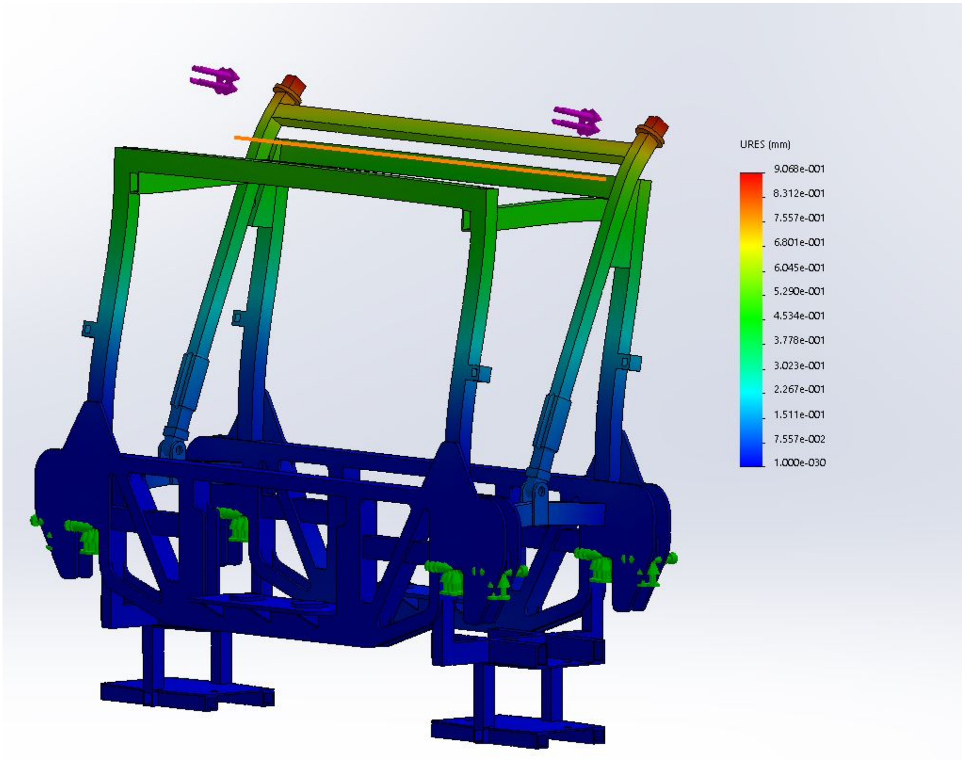

Figure 51:- Displacement plot of the frame assembly with switch as the bogie goes over the gap.

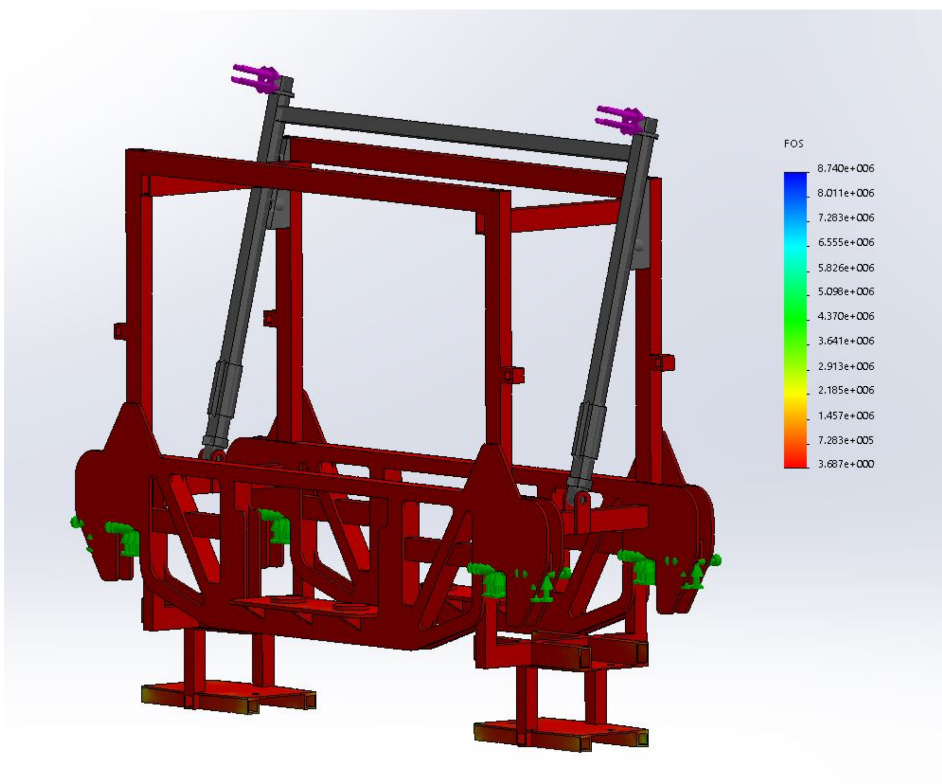

Figure 52:- Factor of safety plot of the frame as the bogie goes over the gap.

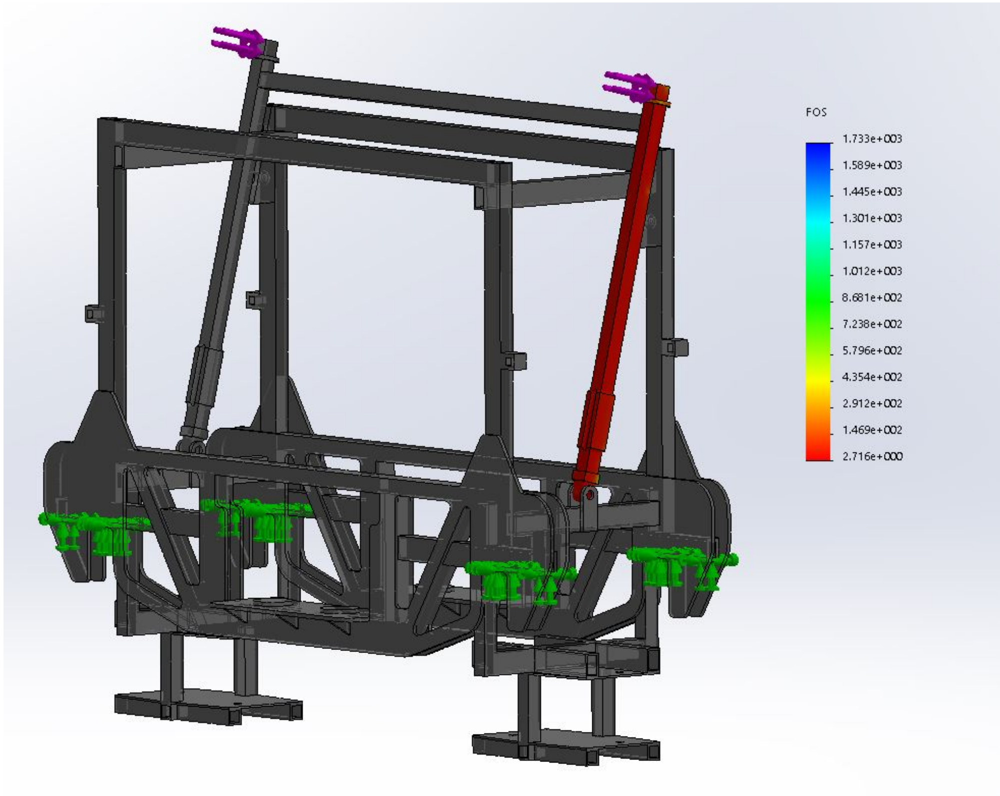

Figure 53:- Factor of safety plot of the vertical switch as the bogie goes over the gap.

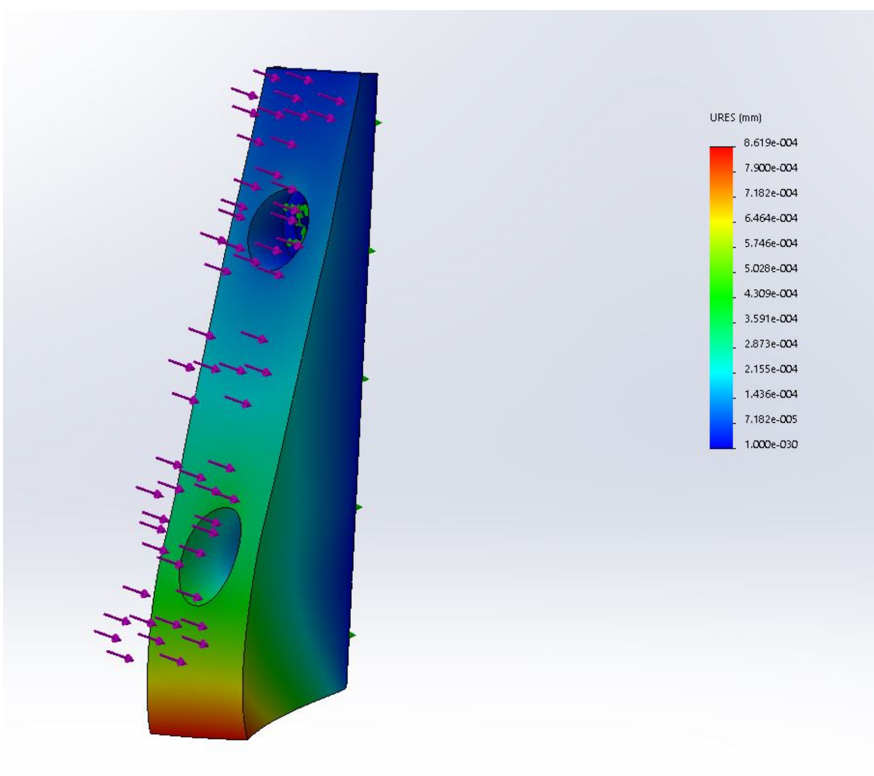

Figure 54:- Deformation in the aluminum support block as the bogie goes over the gap.

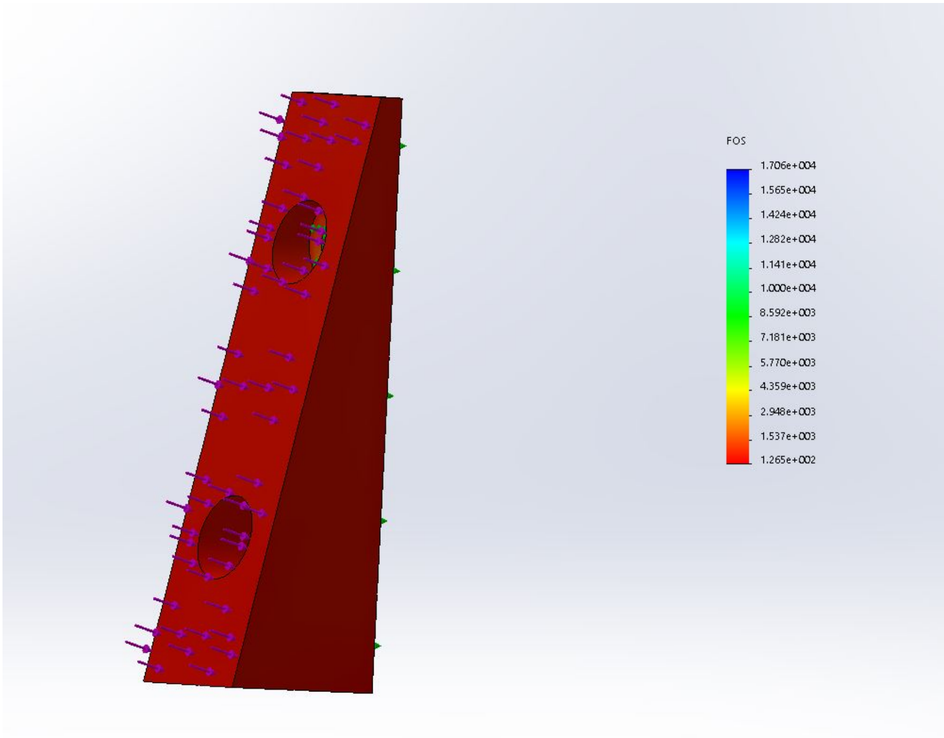

Figure 55:- Factor of safety plot of the aluminum support block as the bogie goes over the gap.

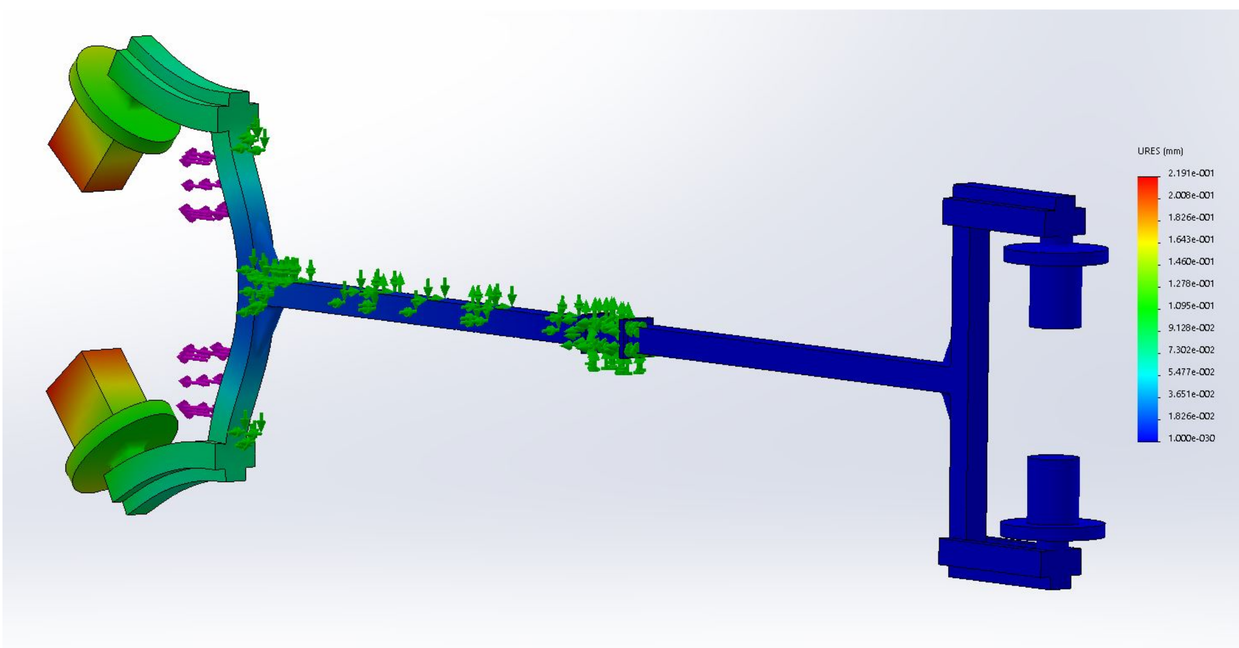

Figure 56:- Slider switch deformation plot under maximum loading conditions.

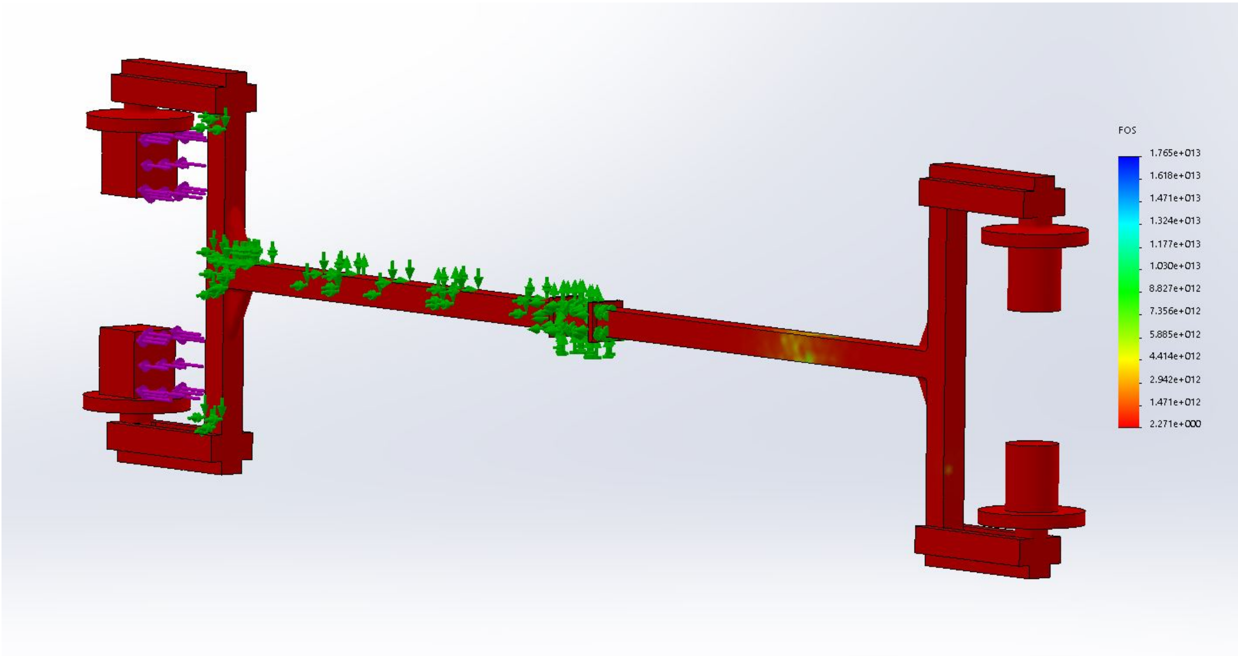

Figure 57:- Slider switch factor of safety under maximum loading conditions.

12.2 CFD Results

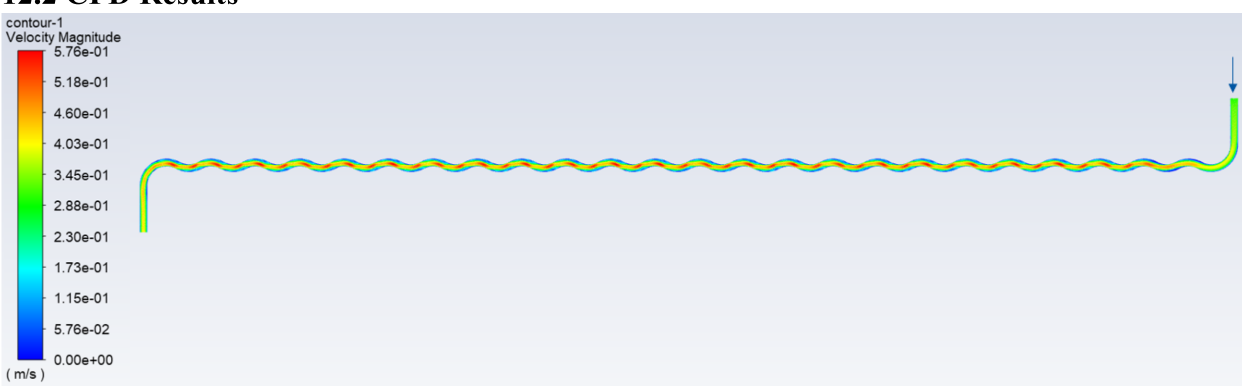

Figure 58:- Velocity contour of 2D CFD analysis using water as a coolant.

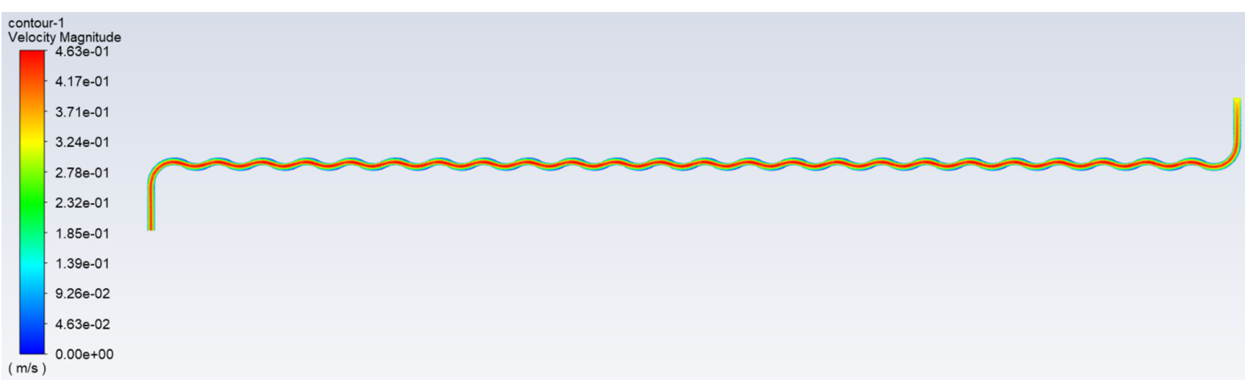

Figure 59:- Velocity contour of 2D CFD analysis using water-glycol mixture as a coolant

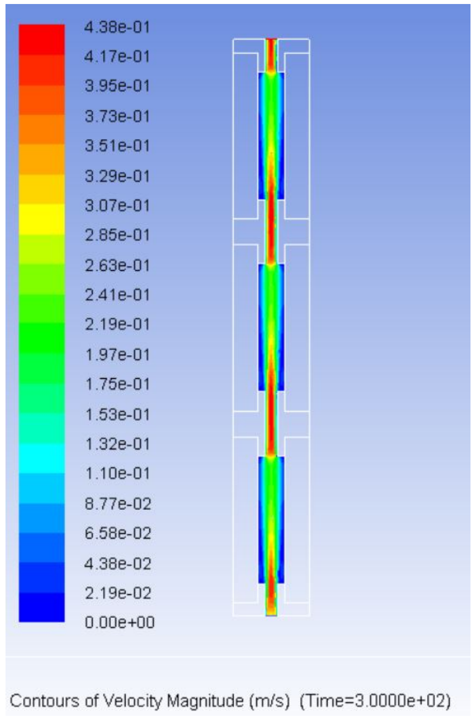

Figure 60:- Velocity contour of 2D CFD analysis using air as coolant

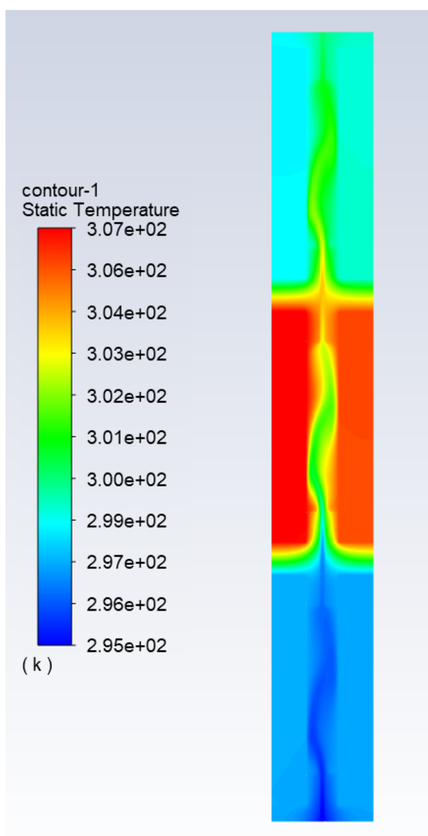

Figure 61: 2D CFD temperature contour for air-cooled pack with 2mm inlet diameter.

12.3 Bill of Materials

Table 2:- 21700 Battery Pack Without Cooling Bill of Materials

Part Number	Part Name	Material	Qty	MFG Process
BP-100-10-010-MS-1	LH Side Frame	ABS	3	CNC
BP-100-10-020-MS-1	RH Side Frame	ABS	3	CNC
BP-100-10-030-MS-1	Brace	ABS	6	CNC
BP-100-10-040-MS-1	G10 Insulator	G10	4	Laser Cut
BP-100-10-050-MS-1	Copper Plate 1 HW	Copper	69	Water Jet
BP-100-10-060-MS-1	Copper Plate 2 HW	Copper	6	Water Jet
BP-100-10-070-MS-1	Busbar	Copper	6	CNC
BP-100-10-080-MS-1	Terminal Busbar	Copper	4	CNC
BP-100-10-090-MS-1	Busbar Cover	G10	6	Laser Cut

Table 3:- Bogie Bill of Materials

Part Number	Part Name	Material	Qty	MFG Process
BO-100-10-010-MS-1	Bogie Frame	AISI 1020	1	Weld
BO-100-10-020-MS-1	Bogie Main Switch	AISI 1020	2	Weld
BO-100-10-030-MS-1	Bogie Slider Switch	AISI 1020	2	Weld
BO-100-10-040-MS-1	Drive Wheel	-	4	Purchase
BO-100-10-050-MS-1	Bogie Base	AISI 1020	1	Weld
BO-100-10-060-MS-1	Motor	-	4	Purchase
BO-100-10-070-MS-1	AL Support	AL 6061	4	CNC
BO-100-10-080-MS-1	Battery Base Plate	AL 6061	1	Water jet
BO-100-10-090-MS-1	Wheel Block	AL 6061	4	CNC
BO-100-10-100-MS-1	Air Bag Suspension	-	4	Purchase
BO-100-10-110-MS-1	Spring Suspension	-	4	Purchase
BO-100-10-120-MS-1	4” Top Wheel	-	2	Purchase
BO-100-10-130-MS-1	3” Slider Wheel	-	8	Purchase
BO-100-10-140-MS-1	6” Guide wheel	-	4	Purchase

12.4 2D Drawings for Major Components

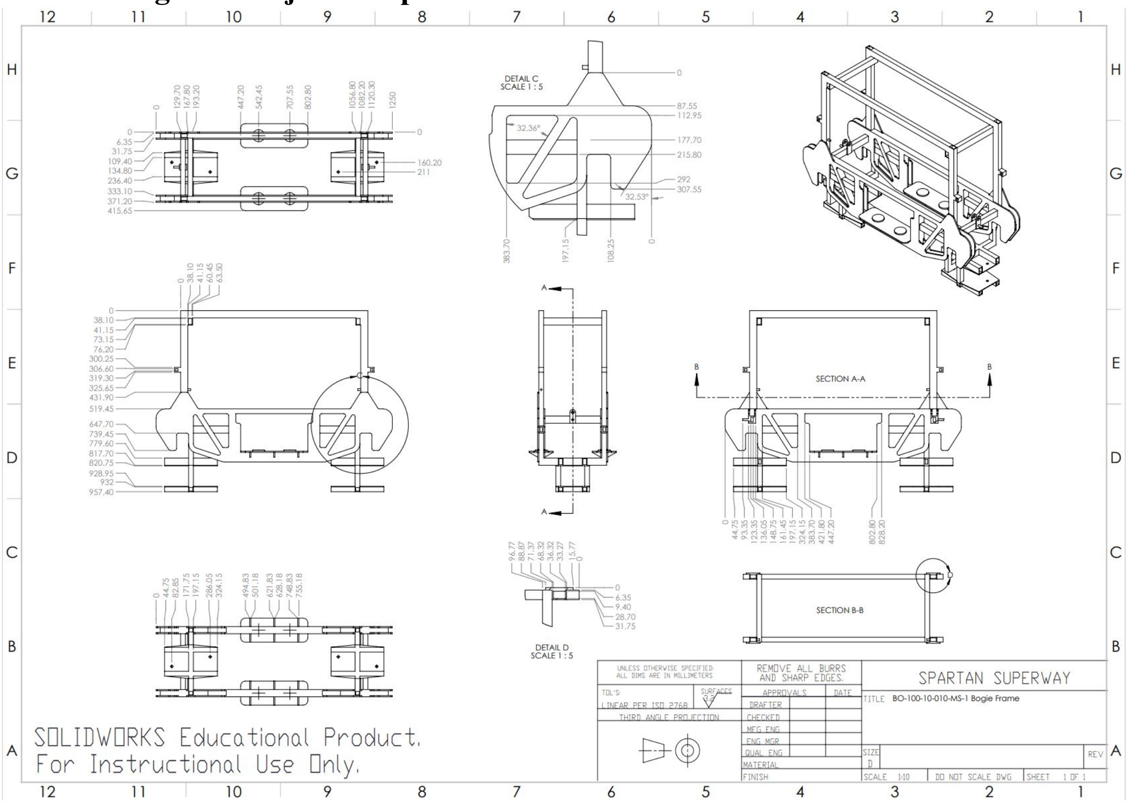

Figure 62:- Bogie Frame 2D Drawing

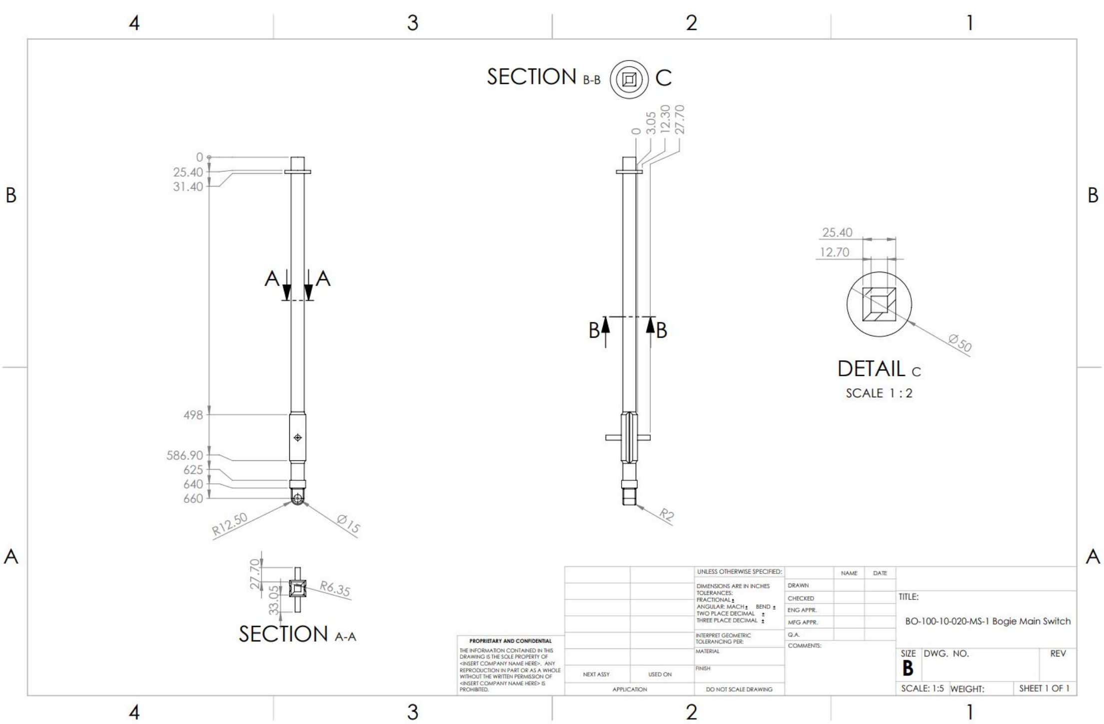

Figure 63:- Bogie Vertical Switch 2D Drawing

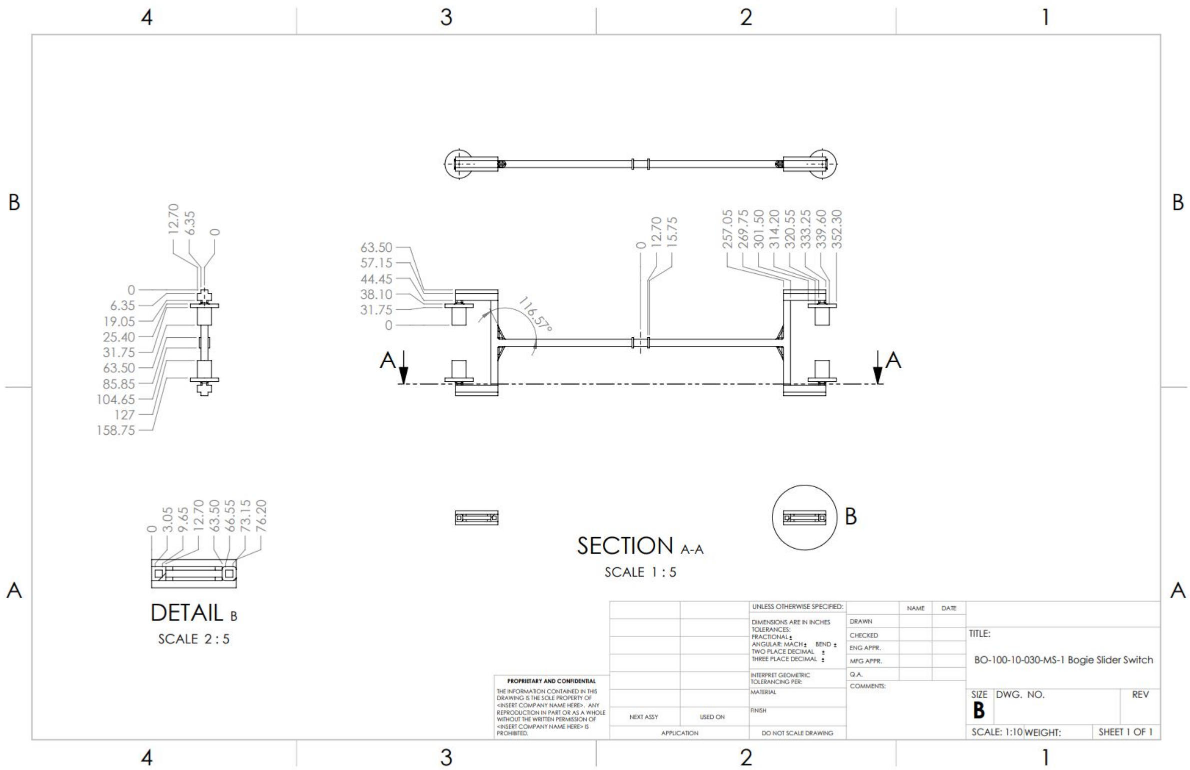

Figure 64:- Bogie Slider Switch 2D Drawing

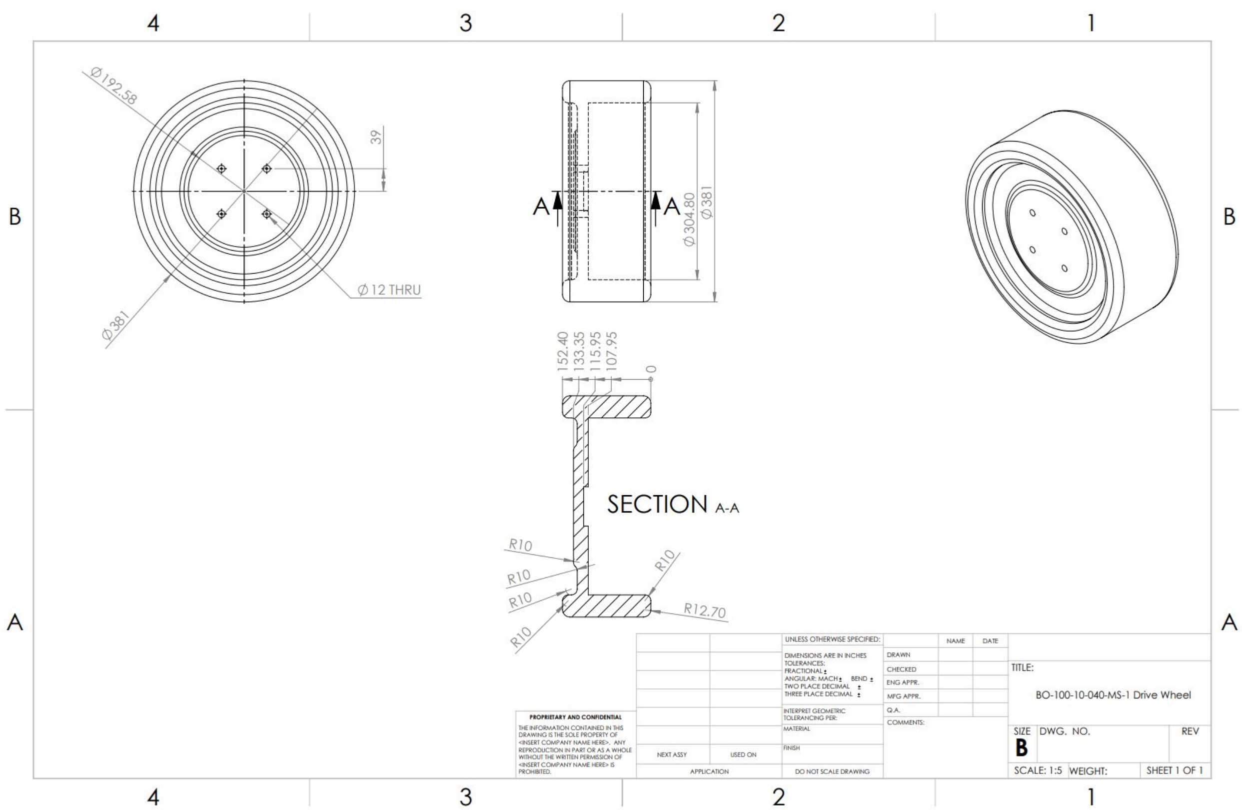

Figure 65:- Bogie Drive Wheel 2D Drawing

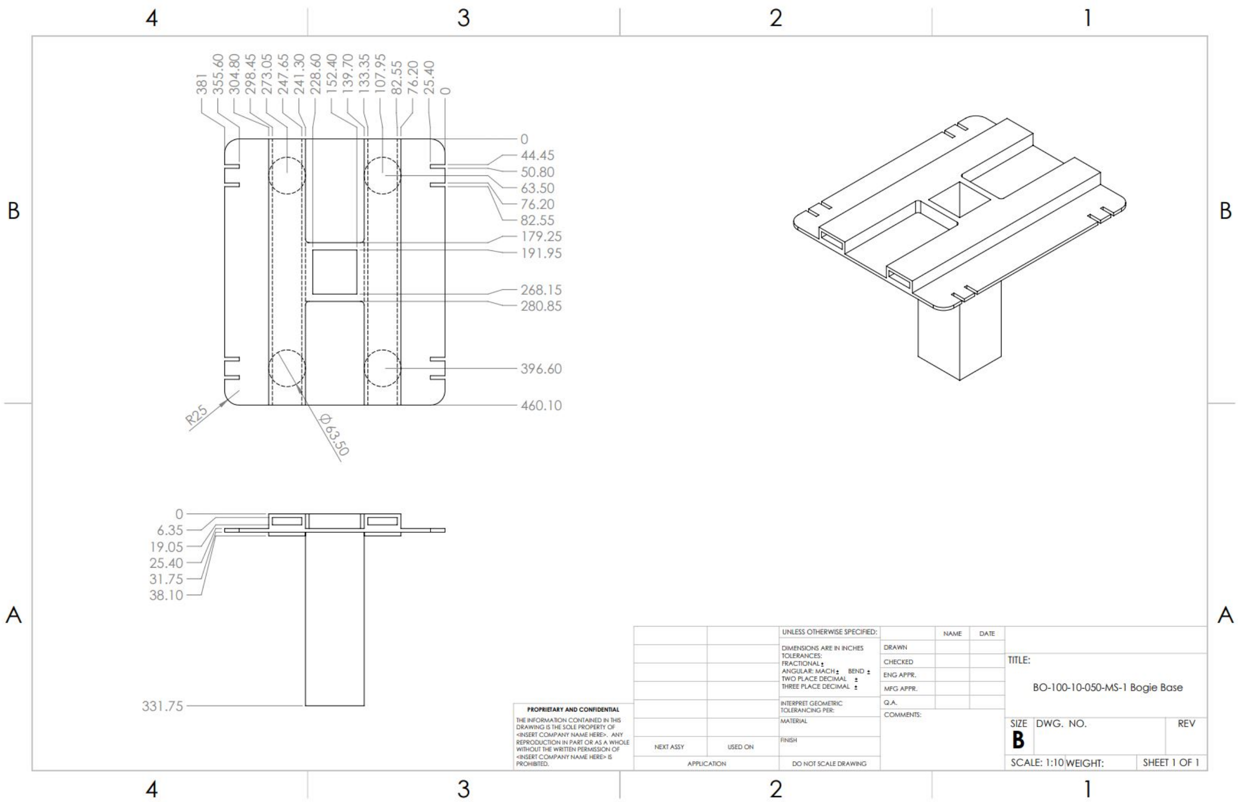

Figure 66:- Bogie Base 2D Drawing

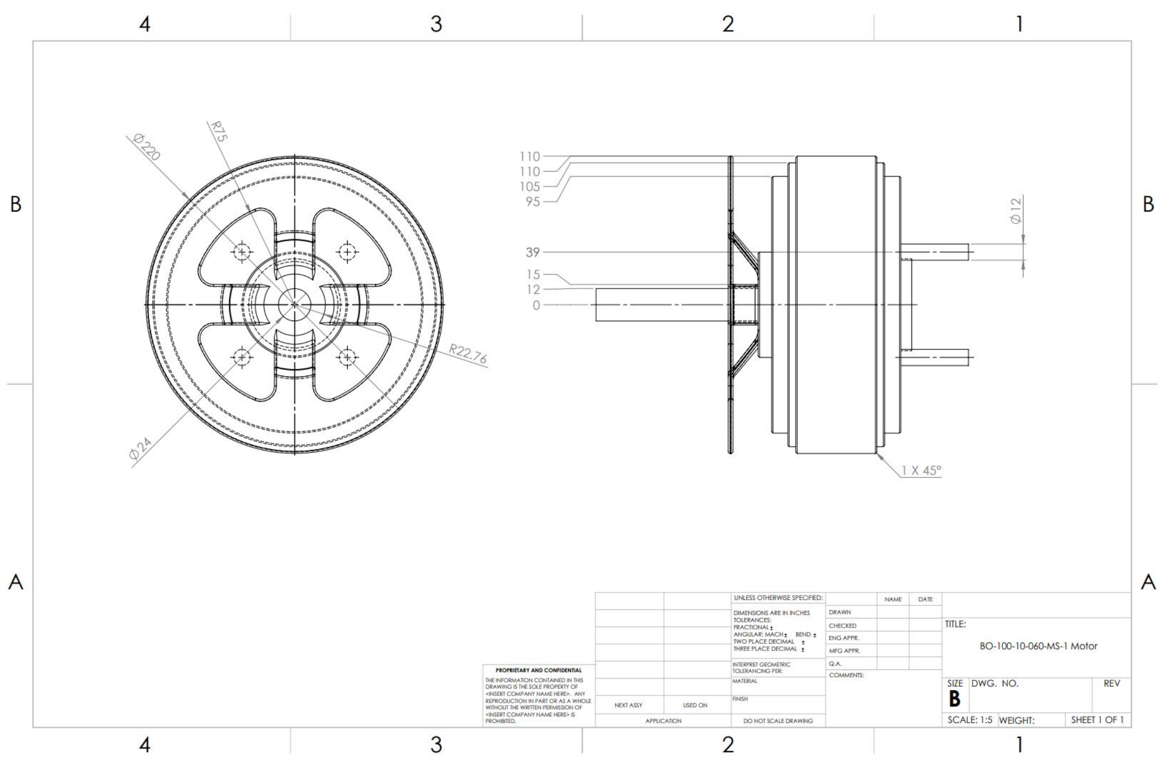

Figure 67:- Bogie Motor 2D Drawing

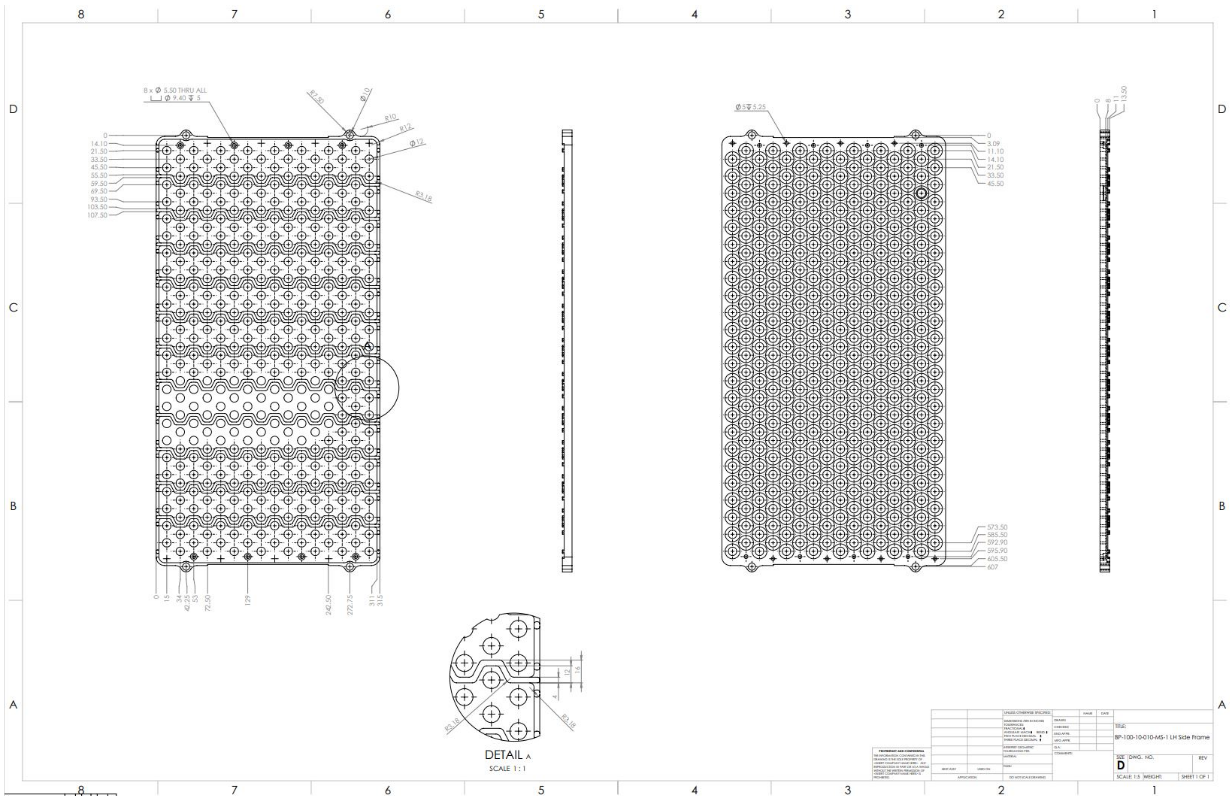

Figure 68:- Battery LH Side Plate 2D Drawing