Superway- A Solar Powered Automated Transportation Network

11m Full Scale Track

San Jose State University
Mechanical Engineering Department
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Advisor:
Ron Swenson
Authors:
Ninebra Babazadehsaralan "Nina"
Jonathan Lagasca
Neeraj Lal

Abstract

Spartan Superway is a student research project striving to create an automated transport network in the bay area. In Spartan Superway there are five teams working together towards a common goal. Teams are: Wayside Power team, Power Module team, Small-Scale Model team, Half-Scale Model, and 11 meter Track team. In the 11 meter track team we are responsible for designing, fabricating and testing the actual track for the assigned bogie of our study. The data collected from our track will be used in order to design and fabricate similar tracks for different studies and projects.

This project is not just for engineers, it is for humanity, because the current climate crisis is everyone's problem. The climate epidemic is of utmost importance in the bay area because the bay has arguably some of the worst traffic congestion in the country and it's one of the sources that it adds up to the current climate change issue. Some put hope in the hydrogen powered/electric vehicle however, the timeline for widespread implementation of such technologies are long. With the Spartan Superway project, this solution to climate change can come as soon as a couple years. The Full Scale Spartan Superway team is here to address the final hurdle in the engineering design process.

Acknowledgements

In a project of this magnitude, the help of extraordinary individuals is quintessential to the success of such a project. In the case of the Full Scale Team, this is no different. First, the team would like to thank Professor Furman for working so closely with the team to find a fulfilling project to complete. All of the Full Scale team members joined late, so from the start the team was at a severe disadvantage. Despite this, Professor Furman helped the team out tremendously to get the team started. Next, the team would like to thank Eric Hagstorm for really helping the entire team stay organized. Despite Eric not being able to be present physically, he does an amazing job in staying in constant communication with the team through email. Lastly, the team would like to send a special thanks to Ron Swenson, Bill James, and Jacques-Hariel, for being the primary advisors on this project. Bill is helping the team out with a bogie, and it was his intern Jacques-Hariel that really started the project out and thought of the modular track design. Ron is sponsoring all of the materials for this project, and the team cannot thank him enough for his constant support and sincere advice. In addition, Ron and his family have graciously donated an amazing space for the enter Spartan Superway crew to research, design, and build their creations.

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I. Executive Summary

The goal for this report is to meticulously document the work that has been completed in regards to the 11m Full Scale Spartan Superway Team. Spartan Superway is an ongoing project that continues year to year, and the primary goal for the project is to help abate the climate crisis that is ongoing. Spartan Superway focuses on making transport autonomous and renewable by utilizing electric solar power. Traffic is a major problem within the bay area, and the transportation system in the bay has seen little change in the last decade. Spartan Superway is here to help solve these problems one team at a time.

In addition, an important goal for the Full Scale Team is to make sure that this track layout is able to be utilized from year to year. In other words, the Full Scale Team wants the track created to be used for testing, so a future team that might need to test out a bogie design, has a functional track to go ahead and test their bogie design on. As a result of teams being able to utilize existing tracks, progress on projects can be expedited. Perhaps, one of the most pressing issues of Spartan Superway is the fact that teams are really never able to make it to the testing phase of their project, and this year's Full Scale Team will help abate that problem for future teams.

As with any research based project, the first step in the entire process is of course research, however, with this year’s Full Scale Team, the research that the team needed to do was considerably less than most. This is because over summer an intern by the name of Jacques-Hariels-Hariel worked on the track design, however he had to leave back to France to return to school. Having Jacques-Hariel around gave the team a massive head start as we were not starting at 0, but rather the team had some previous information to draw upon. In addition, the team worked hand in hand with Jacques-Hariel for a couple weeks before he had to leave, as a result, the project had a solid foundation for the current Full Scale team to build upon.

After the project was handed off to the Full Scale Team, a considerable amount of time was spent truly understanding the previous design. Upon finalization, the actual track layout remained largely the same, some holes were moved around, but the two piece modular design was kept. However, for the uprights, a different approach was taken in an effort to suit the needs of the project further. The final modular track pieces were precisely cut through a high precision water jet located on campus. The material choice for the track is Douglas Fir, and the uprights were designed with 2x4's. All necessary analysis work has been completed and one entire turn of the track has been completed. This upcoming semester the team expects to finish construction of the track and uprights before spring break in an effort to allow for ample testing time on the 11m track. This semester had some massive complications with the ongoing pandemic, but that never got in the way of the Full Scale team.

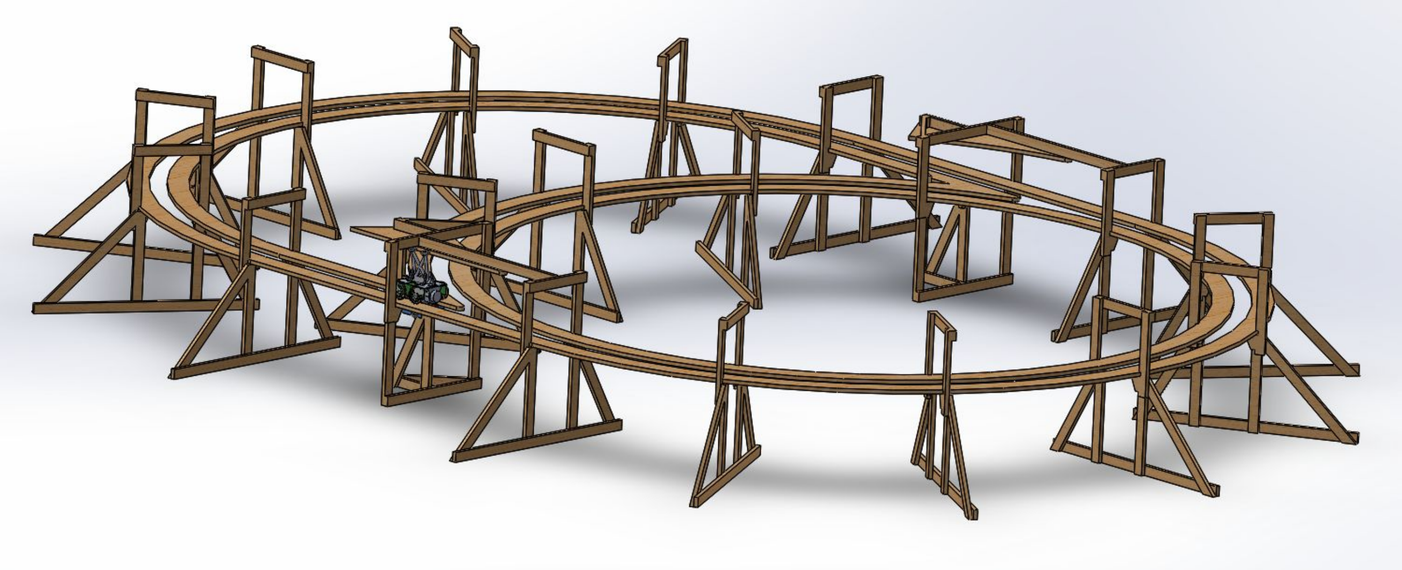


Figure 1: 11m Track with Uprights integrated

Full Scale Team has a unique modular design for the track and uprights which allows for less complexity in manufacturing. This modular track design utilizes two different pieces for the turn section, and one piece for the straight section of the track. The uprights use the same dimensions for the entire track, this is the result of having adjustable ridges for the track to sit upon. In addition, the uprights have adjustable bases and ridges which allow for proper track leveling. As a result of the interchangeable design of the track and upright, this track system is simple to manufacture and easy to maintain.

Throughout the semester, the emphasis was on the upright design as the uprights see many dynamic loads, so designing proper uprights was an arduous task. The track on the other hand was rather simple, and throughout the semester the pieces were being water jetted whenever possible. At this point, it is safe to say about 55% of the track pieces have been water jetted, and about 30% of the track has been assembled. The track currently is resting on tables and chairs and should soon be on the designed uprights before spring break of next semester. The uprights in question went through 2 different iterations before a final design was selected. The final model has been completely analyzed, and the team's analysis work shows where uprights will be needed, and what kind of load the uprights will be withstanding.

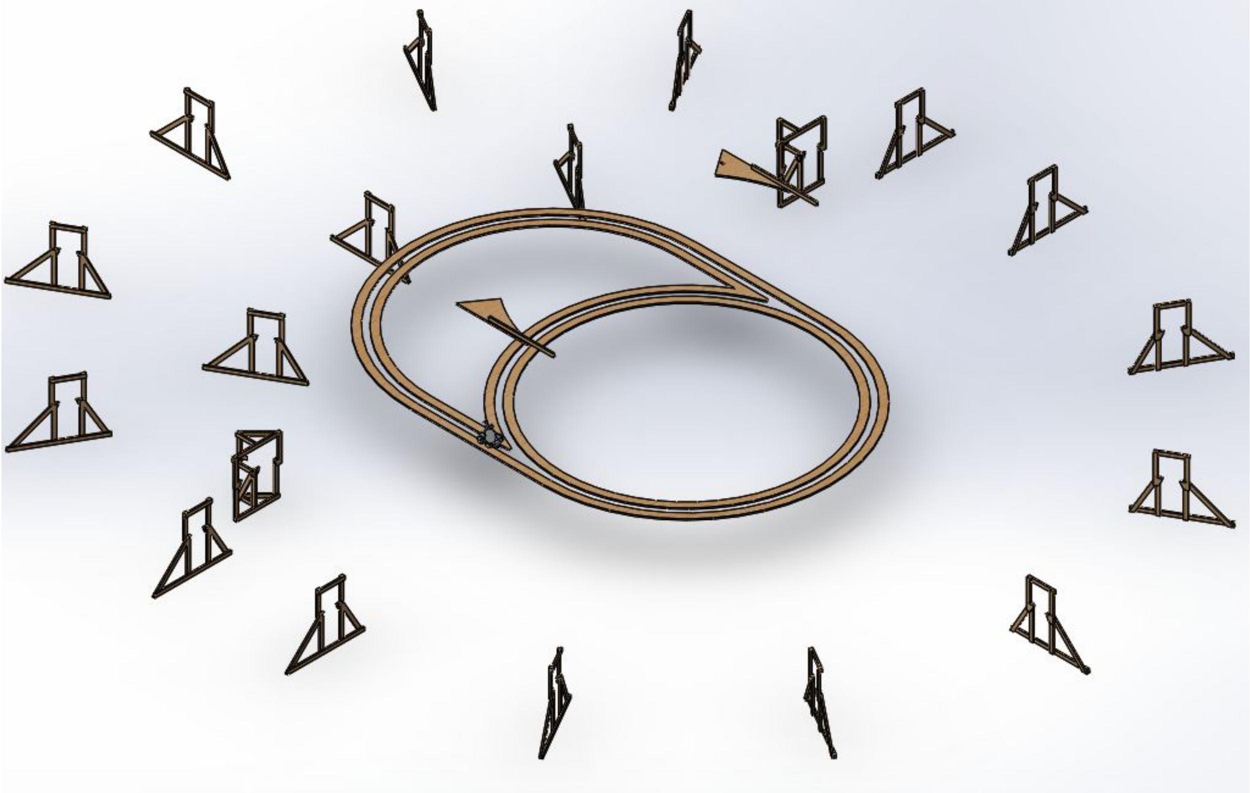


Figure 2: An exploded assembly view showing the track and upright integration

II. Introduction and Project Description

Traffic congestion is a major problem here in the United States, because too many people need to be somewhere at the same time each day. This condition makes roads to have slower speed and longer trip times. As Melissa Bopp and Daniel Piatkowski mentioned in *Bicycling for Transportation* report on Traffic Congestion, they stated that "these traffic congestion causes Americans living in urban areas to travel an extra 6.9 billion hours and consequently consume an extra 3.1 billions of gallons of fuel. This is the problem that has grown since the 1950s, and it keeps getting worse". As the author reported here, we know for fact that traffic congestion is the major problem here in the United States and there should be a solution for it.

Figure 3: Traffic Congestion is a major problem here in the United State

Katherine. "Things to Do While You're Stuck in California Freeway Traffic." Bright Lights of America, 5 Oct. 2015, *[brightlightsofamerica.com/2015/10/things-to-do-while-youre-stuck-in-california-freeway-traffic/.](brightlightsofamerica.com/2015/10/things-to-do-while-youre-stuck-in-california-freeway-traffic/)*

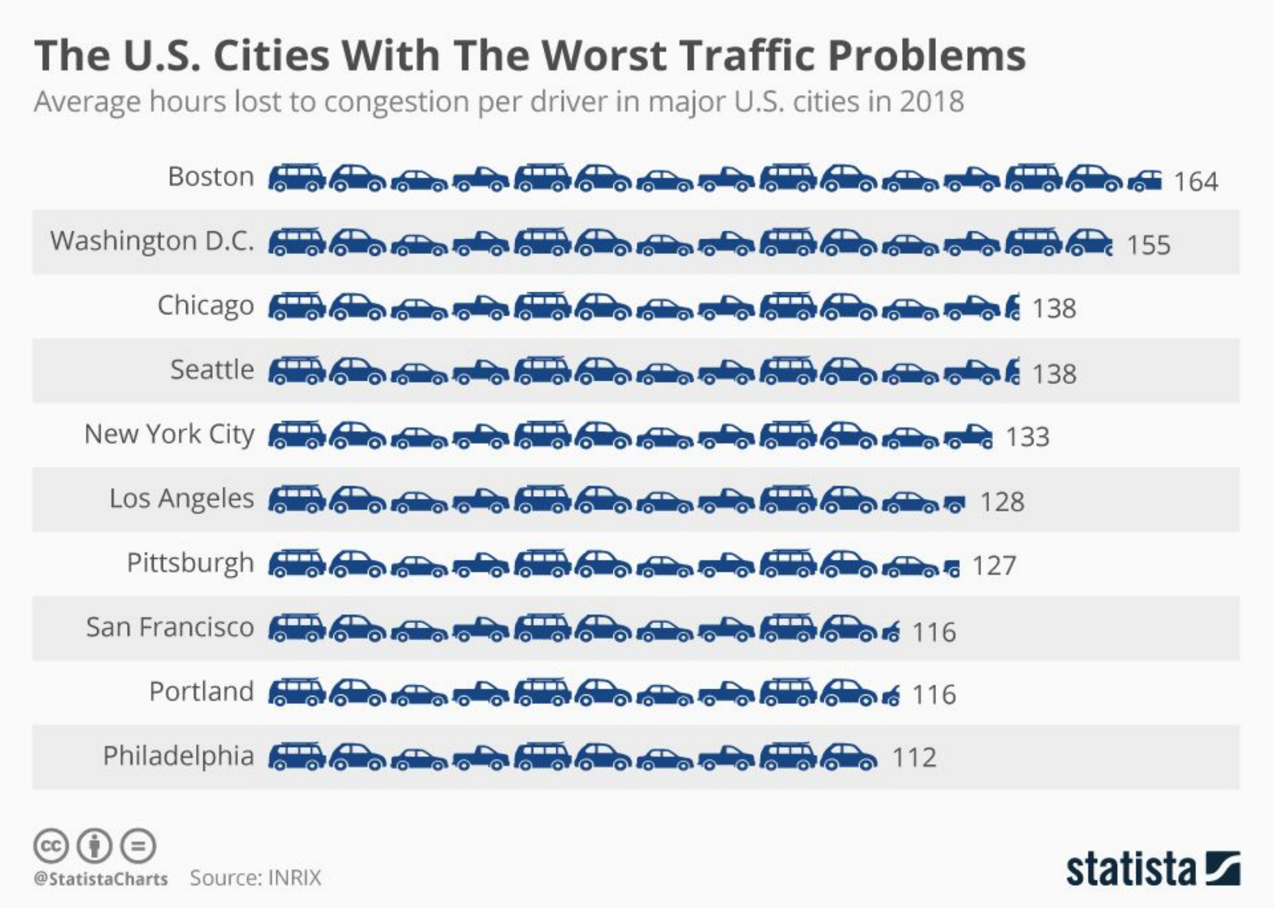


Figure 4: United States cities with the most traffic congestion

McCarthy, Niall, and Felix Richter. "Infographic: The U.S. Cities With The Worst Traffic Problems." Statista Infographics, 13 Feb. 2019, *[www.statista.com/chart/12855/americas-most-congested-cities/.](www.statista.com/chart/12855/americas-most-congested-cities/)*

By having traffic congestion, and roads being filled with cars then the loss of productivity becomes the second major problem here in the United State. People need to use roads to travel and go on with their daily routine, but not being able to manage their time due to the traffic congestion then they lose productivity and time. As Sean Fleming states in his report on Traffic Congestion in the World *Economic Forum,* "the recent research from transport data company INRIX into the state of congestion in 200 cities in 38 countries highlights the impact of snarled traffic by looking at how much time and money it wastes. In the US, it found the total cost of lost productivity caused by congestion to be &87 billion". This report provided the actual number that the loss of hours has cost our nation back in 2018, and it was due to road traffic with no alternative to skip it.

Figure 5: loss of productivity due to traffic congestion is the current problem in the United States

“Transportation and Vehicle Concept - Woman Driving a Car and..” Transportation and Vehicle Concept, 2005, *www.123rf.com/photo_23317876_transportation-and-vehicle-concept-woman-driving-a-car-and-looking-at-watch.html.*

Safety is the number one priority in everyone’s life, but how can a person be 100% safe if he/she has to spend hours and hours of the day going through roads that are blocked with traffic and accidents? The number of new drivers taking the road is way larger than new roads being built, this means that there are more drivers sharing less space which leads to traffic congestion, loss of productivity and car accidents. Benjamin Schneider in his report for CityLab University: Induced Demand mentioned that “in rapidly growing areas where roads were not designed for the current population, there may be a great deal of latent demand for new road capacity, which causes a flood of new drivers to immediately take to the freeway once the new lanes are open, quickly clogging them up again”.

In the United States, deaths resulting from traffic accidents outweigh the toll taken by two most deadly diseases such as cancer and heart disease. Based on the Current Understanding of the Effects of Congestion on Traffic Accidents report by Angues Eugene Retallack and Bertram Ostendof, it is obvious that the “traffic accidents impart both economic and social costs upon communities around the world:. which is why, the deaths on road due to traffic congestion is becoming another major problem here in the for United States and it needs to be resolved in order to save people's lives.

Figure 6: car accidents - the number of death and injuries increases every day due to traffic congestion

Williams, Burnett. "Who's at Fault in a Multi-Car Accident?: Virginia Personal Injury Lawyers." Who's at Fault in a Multi-Car Accident?, 19 Oct. 2018, [burnettwilliams.com/whos-at-fault-in-a-multi-car-accident/.](burnettwilliams.com/whos-at-fault-in-a-multi-car-accident/)

After all, the climate crisis driven by greenhouse gases is the reason that our earth is in danger. Human activities are the reason for increasing greenhouse gases into the atmosphere for the past 150 years. Burning fossil is the main greenhouse gas emissions, and there are many sources that emit greenhouse gases into the atmosphere daily, but the transportation sector generates the largest share of greenhouse gas emissions. The United States Environmental Protection Agency reported that "transportation activities, in aggregate, accounted for the largest portion (28.9%) of total U.S. greenhouse gas emissions in 2017. This large number comes from burning fossil fuel for cars, trucks, ships, trains, and planes which is a danger to our planet, society, and environment.

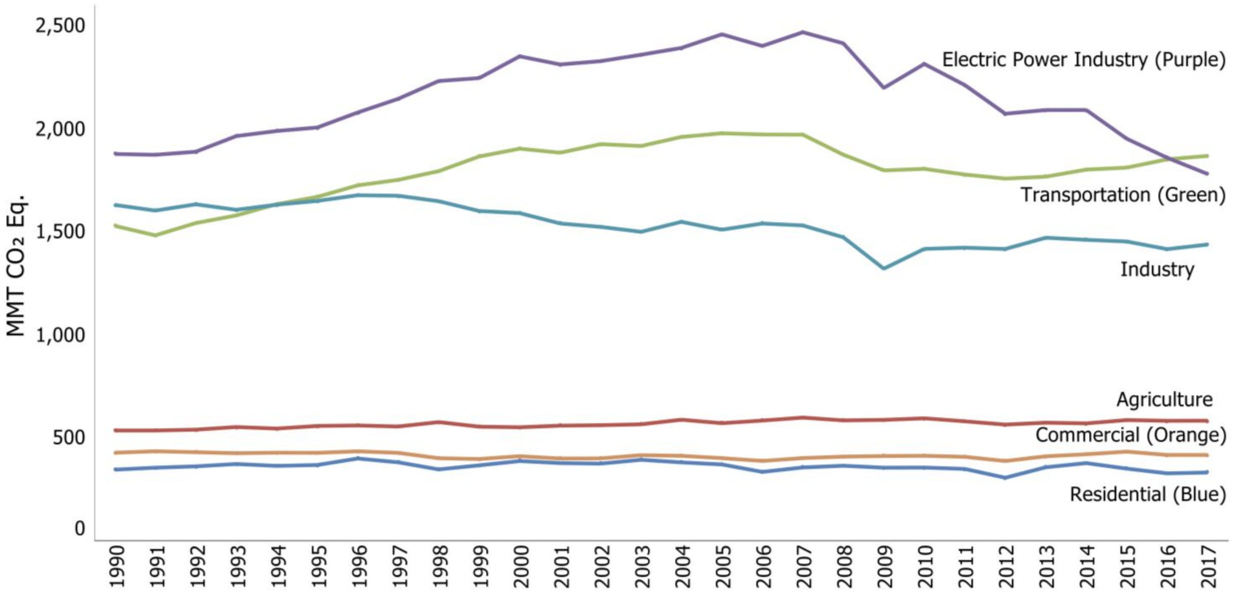
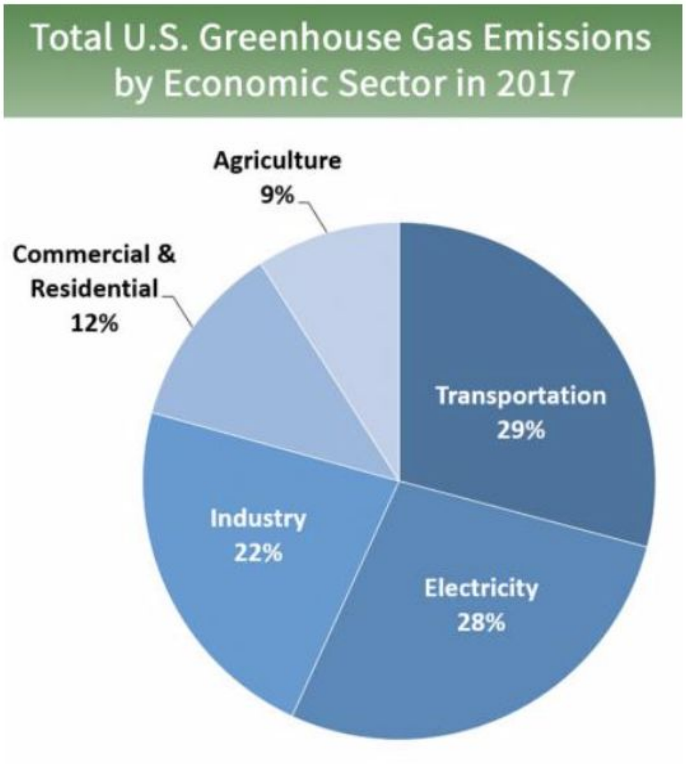


Figure 7: greenhouse gas emission is a threat to climate change

United States Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks. 2017,

www.brown.edu/Departments/Economics/Faculty/Matthew_Turner/ec1340/readings/us-ghg-inventory-2019-main-text.pdf.



Total Emissions in 2017 = 6,457 Million Metric Tons of CO_2 equivalent. Percentages may not add up to 100% due to independent rounding.

Figure 8: Total United State greenhouse gas emissions by economic sector in 2017

United States Environmental Protection Agency. "Overview of Greenhouse Gases." Greenhouse Gas Emissions, 10 Apr. 2020, www.epa.gov/ghgemissions/overview-greenhouse-gases.

Once again, the traffic congestion is the reason that our environment has a large amount of greenhouse gas emissions daily. Traffic congestion leads to blocked roads, unsafe roads, and non-clean energy use roads. Therefore, the societal needs for and impacts of improvements in urban transportation.

When someone thinks of the traffic congestion problem, she/he immediately comes up with an idea of adding more roads. As mentioned earlier, the number of new drivers taking the road increases every day, therefore adding new roads may not be the best solution. Also, adding roads might help to reduce the current traffic problem that leads to blocked roads, but it will increase the danger to climate change. If the number of roads increases, then the use of fuel burning transportation will also increase, which is a death to our world. by adding more greenhouse gases into our atmosphere, then we increase the danger of climate change which simply means the end of the world. The solution that will help thi9s major problem of our society has to fix all current problems, such as: traffic congestion, road's safety, climate change.

Spartan Superway understands the major problem of our society and gathered a team that can help to put a stop on harming our society, environment, and basically our world. The Spartan Superway system solves the major problem of traffic congestion by designing a solution that helps with traffic on the road, block roads and unsafe roads due to traffic, and more importantly the climate change.

The safe roads begin with Spartan Superway. Here at Spartan Superway all teams work together to complete the design that can benefit the consumer and society itself. This is the solution that helps people with getting their daily routine done, while it has zero danger to our environment. By using this new way of transportation the society and its population will live longer, helatir, and happier.

Figure 9: Spartan Superway with its clean energy source

"Spartan Superway." Spartan Superway Development a White Paper , San Jose State University, 14 Mar. 2017, *www.advancedtransit.org/wp-content/uploads/2017/07/FurmanSwensonHagstrom.SpartanSuperwayWhitePaper.SpartanSuperway.pdf.*

This autonomous transportation idea is helping with traffic congestion and roads getting blocked because it uses its own track. The track is not sharing a space on the main roads with other transportation systems; therefore, more people are able to travel during the day without sharing the same road with others.

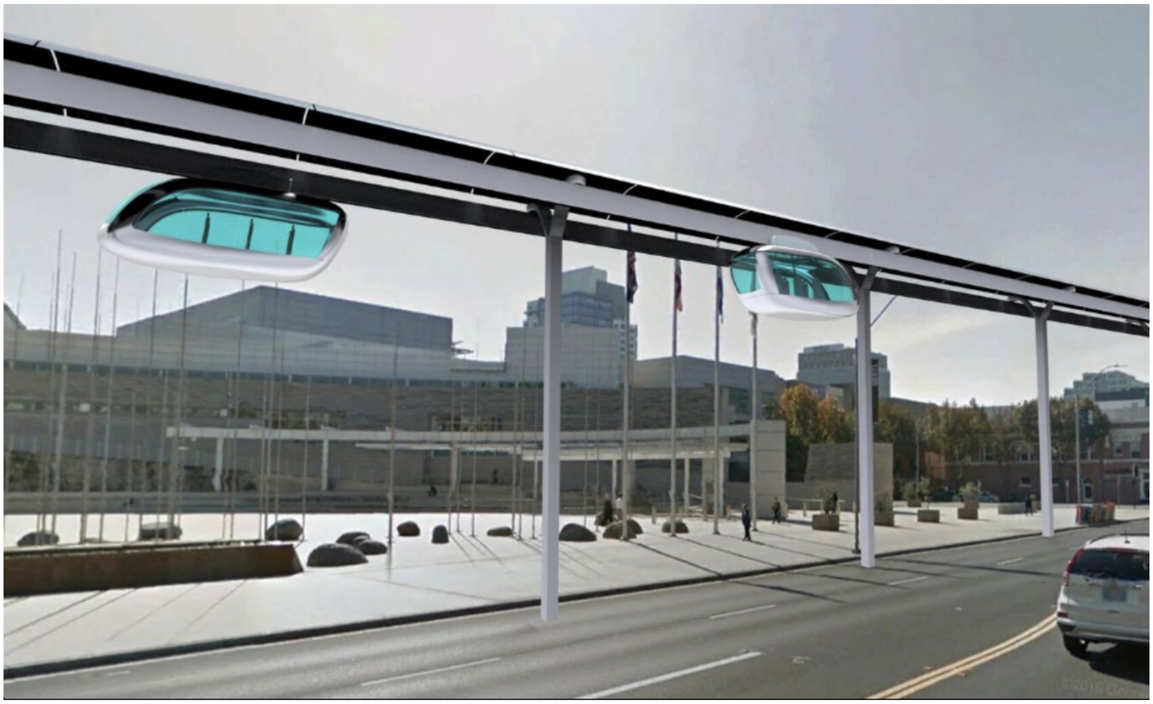


Figure 10: Spartan Superway track idea for the future

Swenson, Ron, et al. "Solar Skyways Network." Solar Skyways Network, San Jose State University, 23 Nov. 2017,

www.solarskyways.net/2017/.

Being able to travel without sharing roads with others can help to decrease traffic on the main roads. In this case, roads won't get blocked and the safety of roads will increase. Based on the CARSURANCE report there are nearly 40,000 fatal car accidents per year in the United States, and each day more than 90 Americans die in accidents. Also, 2 million drivers experience a permanent injury everyday. This report proves that roads are not a safe place anymore, but

Spartan Superway is here to solve this for the better. This new way of transportation keeps our roads safe and decreases these reported numbers of death and injury due to an accident. Spartan Superway is the solution that will create a report of zero injury and death due to car accidents.

Figure 11: safe roads when more transportation system being used such as Spartan Superway

Tan, Christopher. "Fewer Accidents as Roads Are More Free-Flowing Now." The Straits Times, 14 May 2020,

www.straitstimes.com/singapore/transport/fewer-accidents-as-roads-are-more-free-flowing-now.

Another good benefit of using Spartan Superway is saving time and being productive. People spend hours and hours of their day sitting through traffic, but using Spartan Superway helps people to travel and reach their final destination without wasting their valuable time. This is the solution for people to become more productive with the time they save by not getting stuck in traffic.

Figure 12: saving time and being productive by using autonomous transportation

Rampton, John. "So, Are You Busy? Or, Are You Productive?" How Productive Are You? Here Are 8 Ways That You Can Find Out, 11 July 2017, due.com/blog/productive-8-ways-find/.

More importantly Spartan Superway is here to help with climate change. The team is working to have autonomous transportation that uses clean energy. Spartan Superway has zero harm to the environment since it's using clean energy. Spartan Superway burns no form of coal and there are no greenhouse gas emissions into the atmosphere; therefore, the threat to climate change is gone with Spartan Superway. Other transportation such as: cars, trains, airplanes are burning fossil fuel for their fuel which they add a large portion of greenhouse gases into the atmosphere. Furthermore, Spartan Superway is absolity clean energy user and it's an autonomous transportation that reuse its clean stored energy. On the Spartan Superway team, we believe we have the solution to the current mobility problem, and our goal is to have everyone in our environment to join us and help to save our society, our environment, and our world.

Figure 13-a: use clean energy will save our world

Fullbrook, David. "Keeping It Clean." Renewable Energy a Better Way for Myanmar, 18 Feb. 2016,

www.mekongeye.com/2016/02/18/keeping-it-clean-renewable-energy-a-better-way-for-myanmar/

Figure 13-b: renewable source of energy that help our planet

Ciera. "Renewable Resources: The Impact of Green Energy on the Economy." Experience the Art of Energy, 3 Nov. 2017, www.solcoast.com/renewable-resources-impact-green-energy-economy/.

III. Objectives

The 2020 Spartan Superway Full Scale Team will design and build the 11 meter track. Our purpose is to have a track available for our designed bogie to test and improve for better. From August till December of 2019 we have been working on design for the track and uprights. For this reason, we started water jetting track pieces and put together the overall track. Our goal is to have the designed track with its upright done by March of 2020, in this case, we are able to test and run the bogie. From March to May of 2020 we will be testing the bogie on our designed track to observe any failure, so that we can improve it.

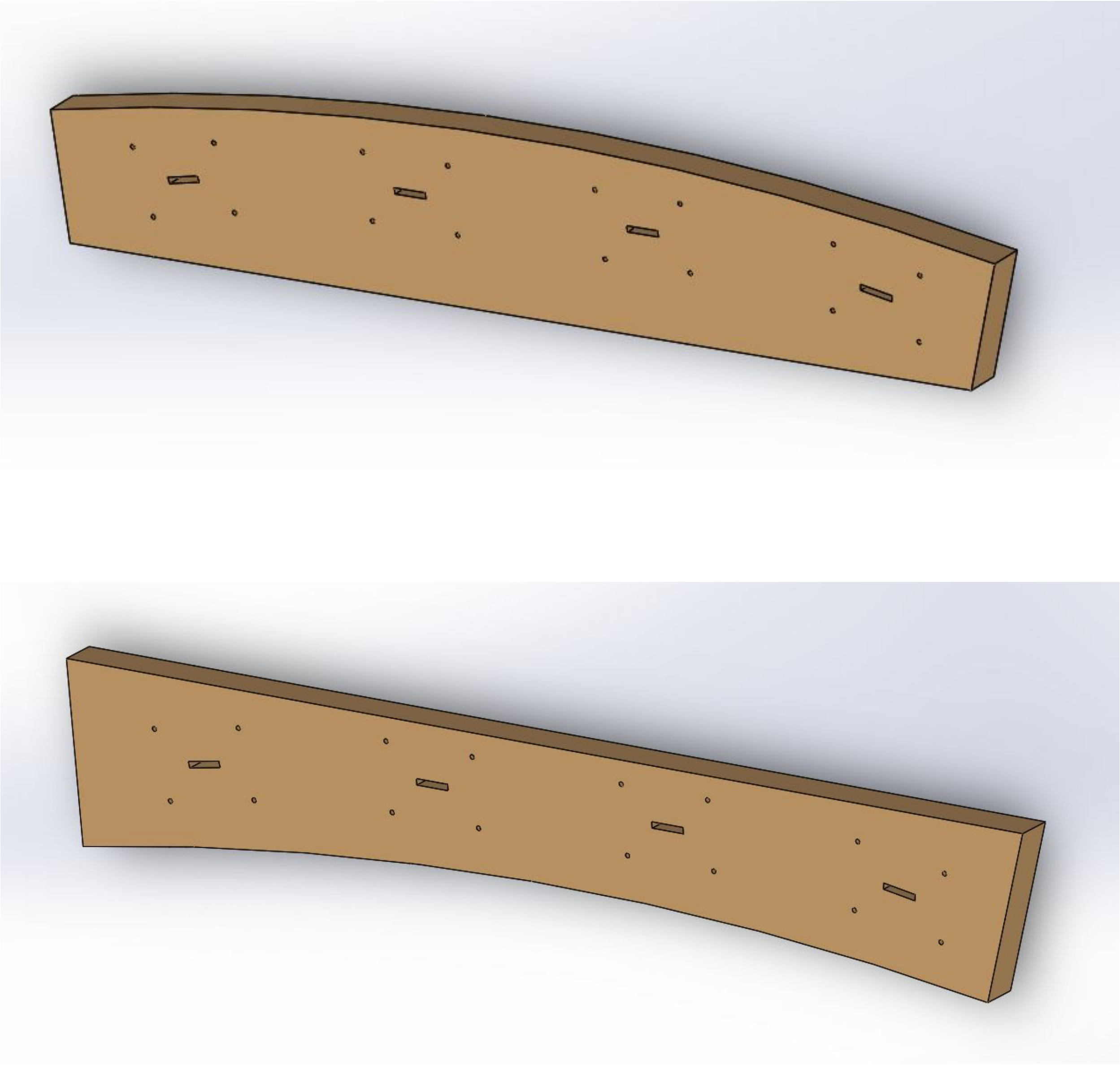


Figure 14: The CAD drawings above show how the track pieces have to be water jetted

Since our team is the first team to design and build the tack for the specific bogie, so we had to use a material that is easy to use, easy to find, and cheap to purchase. Therefore, we used Douglas Fir Wood that is available everywhere and cheap to purchase. Also, the reason we choose wood for our track is because we wanted to be able to hand cut the pieces if we aren't able to use the water jetting system at San Jose State University.

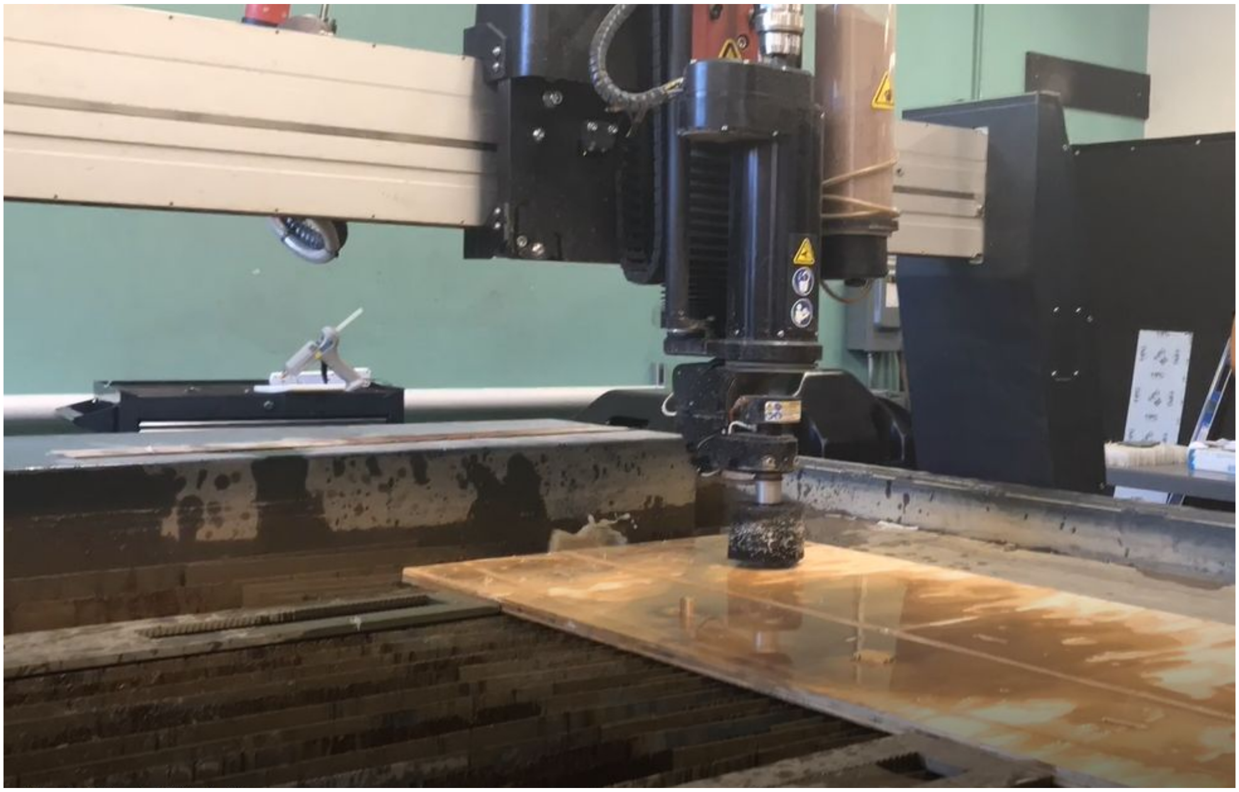


Figure 15: The water jetting system used to cut the track pieces

Figure 16: The device used to cut the track pieces when water jetting isn't available

Our team did not have a set budget for our 11 meter track (Full Scale Team), but we have had support from our sponsor Mr. Ron Swenson. He was providing our supplies for our track and everything we needed for our project for the Fall of 2019, and he is willing to give us his support for the Spring of 2020 as well. So far our expenses for this 11 meter track was $1285 which covers the woods for the track and its uprights. The prices broken down are in appendices.

IV. Structure of Project

The 11m Full-Scale Track is divided up into two divisions: the track assembly, and the uprights holding the track. The track assembly consists of the bogie, track pieces, and the switching mechanism. The track assembly mainly consists of two waterjet parts. This is mostly handled by Jonathan, but Nina and Neeraj substitute for him when he is not available. The switching mechanism is mainly a task that has the support of external assistance. Bill James of JPods and Carlos Ortega will be assisting Jonathan in creating a functioning switching mechanism for the 11 meters track.

In order to design the uprights, the forces that would be applied during operation had to be calculated. Nina and Neeraj are in charge of the upright design and placement. Nina is in charge of designing the upright alongside Neeraj, but Neeraj will create the first working upright. Nina and Neeraj will both produce as much uprights needed to support the track by the end of the project.

V. State of the Art/ Literature Review

ATN Technology

Automated Transit Network(ATN) is a technology that has existed for a long amount of time. There is a 7-point definition of ATNs as established Advanced Transit Association (ATRA), (Ellis).

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 vehicles (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 their 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
   ATN tech at SJSU since 2012

As of 2014, 5 examples of ATN exist and will be discussed in this section.

The Morgantown PRT is one of the first iterations of an ATN in West Virginia University. It consists of a straight, linear railway that has passenger cars with a capacity of 8 to

20 persons.

Figure 17: The Morgantown PRT in West Virginia University

Wvutoday. "WVU Today: West Virginia University's PRT Resumes Operation for Spring 2019 Semester." WVU Today | West Virginia University, West Virginia University, 7 Jan. 2019,

wvutoday.wvu.edu/stories/2019/01/07/west-virginia-university-s-prt-resumes-operation-for-spring-2019-semester.

Masdar PRT has been operating in Masdar City, Abu Dhabi since 2010. This ATN again uses magnetic rails, but also has lithium-battery powered cars. These cars carry 4 adults and 2 children.

Figure 18: Masdar PRT in Masdar City, Abu Dhabi

The National. "Masdar to Expand Its Autonomous Vehicle Network." The Driverless Vehicle Network Will Be Expanded along a New One-Kilometre Route, 16 Jan. 2018, www.thenational.ae/uae/transport/masdar-to-expand-its-autonomous-vehicle-network-1.695985.

The ParkShuttle system is another example of an ATN in the Netherlands. The system consists of bus-like passenger cars that move along magnetic rails. Each car can carry 12 passengers.

Figure 19: The ParkShuttle system in Netherlands

Angevaare, Frans. ParkShuttle . 15 Feb. 2018,

www.flickr.com/photos/55286387@N05/39385982095.

The ULTra PRT system operates in Heathrow Airport in London. These passenger cars operate on an elevated railway with occupancy of 4 passengers and luggage.

Figure 20: ULTra PRT system operates in Heathrow Airport in London

Phenix, Matthew. "There's a Secret Way to Try Out Driverless Cars at Heathrow Airport." AFAR Media, AFAR, 4 June 2018,

www.afar.com/magazine/take-a-ride-in-heathrow-airports-secret-driverless-cars.

Lastly, the Skycube system in Suncheon Bay, South Bay has operated since 2013. It consists of a linear guideway like the Morgantown PRT between two stations. The cars carry 6 passengers.

Figure 21: Skycube system in Suncheon Bay

Choi , Kyu-Sang. "SkyCube." SunCheon PRT : SkyCube Project Overview & Operation Status , Oct. 2015,

www.advancedtransit.org/wp-content/uploads/2015/12/Suncheon-PRT-edited_Podcar-City-9th.pdf.

In all of these ATNs however, they do not fully utilize the capability of reducing cars on the road and saving the environment. Their routes are restricted as specifically the Skycube and Morgantown PRT, with their linear routes. If the routes could be expanded upon, then the full benefits of ATNs could be obtained.

Spartan Superway ATN Previous Works

In the 2015 Full-scale report, the upright design was greatly modular, the team made great strides on keeping a low deflection of their track design. This was mostly due to the sturdier material chosen for their upright, which was metal unlike this year's wooden design.

Full-scale 2016 team's track had a steel and concrete-reinforced design for their uprights. This is good in that it produces lower deflection, but reduces this current year's goal of maintaining ease of manufacturability and modularity.

The team of 2017 & 2018 both had designs that used metal shafts which ease manufacturing, but this still conflicts with this year's goal of using easy-to-gather materials. However the 2018 team had solar panels, which would be of great use for the track in the future, for increasing sustainability.

SJSU Full-Scale Subteam Previous Works

Though this is a full-scale team, this idea of a platform to test on has not been an idea in past years or literature in San Jose State University. Past works usually consist of creating a scaled model of the superway, but no project has been a direct platform to just test designs. This project will be the first of its kind, and will aid in the design of other teams to come. However, this project can make use of the methods that other teams have used in their design process, such as FEA analysis on uprights, loading calculations, and features of upright design.

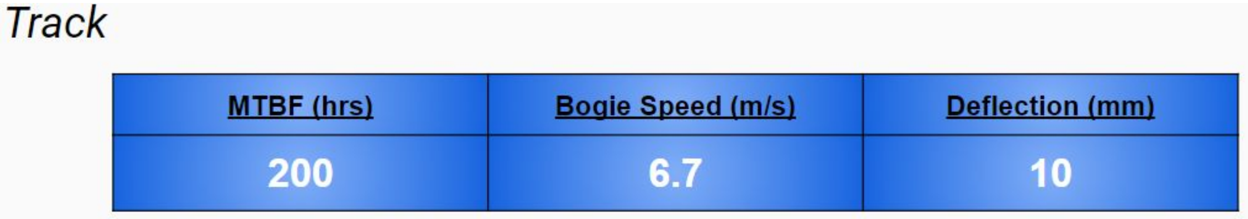
VI. Design Solution/Analysis

Background

Before jumping into the final designs of the upright and track it is important to discuss the design goals that both the track and upright must meet, and how the current design fits into these design goals. After that, previous design considerations will be explained, and lastly, this section will discuss the final designs and why they were the best.

Track Design

The track design had to fulfill a variety of different design goals. First, the track needs to be able to support the weight of the 44kg bogie. It is important to note that this specification is different from the upright design specification. In other words, the track needs to support the weight of the bogie traveling at speed in between uprights. The specific design specifications for the track can be seen in Figure 22



Track

MTBF (hrs)	Bogie Speed (m/s)	Deflection (mm)
200	6.7	10

Figure 22: Design goals for the Track to undertake when designing

In track designs the fewest uprights is most ideal, and because of that, it was an important design consideration for the team that the track has as few uprights. In addition, cheap manufacturing was also an important consideration, so in order to both be cheap but still be strong enough to have fewer uprights, 0.7” thick plywood was selected as material. Second, the track needs to be able to accommodate a multi-wheel bogie design. As a result of the bogie needing to support a multi-wheel design, the track was designed to be flat with an outside and inside piece. The tracking being flat allows for the multi-wheel bogie design to lay on top with secondary wheels on the side pushing against the track. The bogie in question is being supplied by Jpods, and this design specification was given by them. The reason the bogie needs to be a four wheel design as explained by Bill James (Private Communication), from Jpods is, to help with bogie stability and pod support. Jpods is a design company that focuses on sustainable autonomous forms of transportation similar to Spartan Superway.

The track assembly will mainly consist of two track pieces: an inner piece and an outer piece. These pieces will help accomplish the goal of being able to simplify manufacturing, as well as reduce production time. The inner piece will be made of the same douglas fir wood as the outer piece. The track parts will be arranged with slots to allow for aligning of the track parts, and then glued together or with bolts if needed. They will be arranged in a staggered pattern, akin to that of legos.

The switching track parts will be attached to the track as static parts as the switching mechanism will be on the boogie. This 11 meters track’s switching mechanism will emulate that of the small-scale track where modular track parts will be supported at a higher height than the base track pieces to allow for the switching of the bogie.

At minimum the bogie will have 11 wheels, 8 wheels to keep the bogie stabilized vertically to keep attached to the top and bottom of the track. Two wheels will be placed in between the inner and outer track pieces to keep the bogie stabilized vertically. Lastly, one wheel will be attached to a servo and will contact the switching pieces of the track.

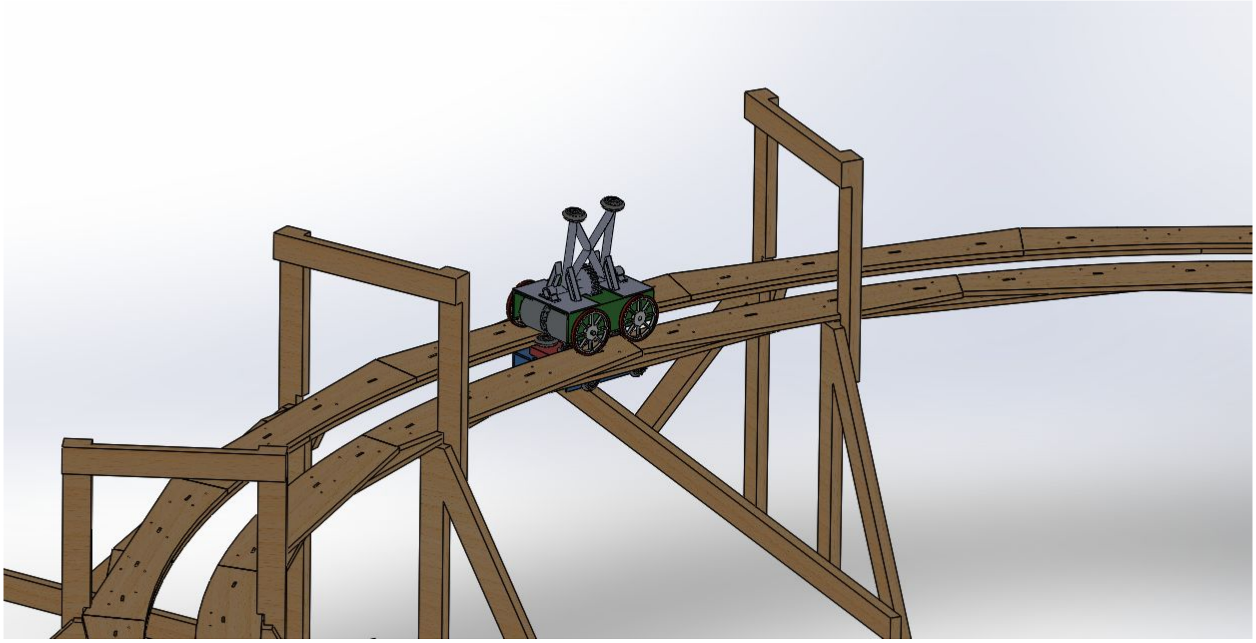


Figure 23: The CAD drawing above shows the way each track piece interacts with each other

Figure 24: Pictured is the mentioned track pieces and uprights at the Spartan Superway Design Center

Track Analysis

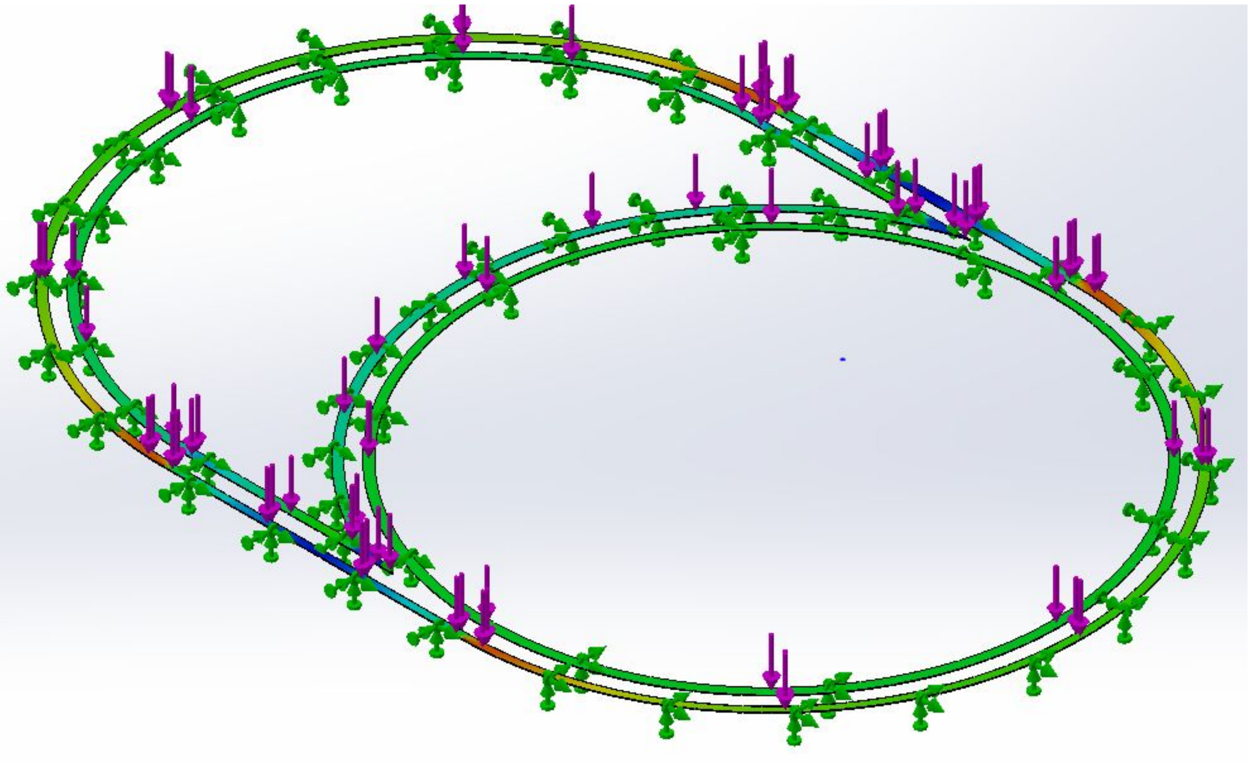


Figure 25: Former FEA Study on Track: 1.4mm deflection

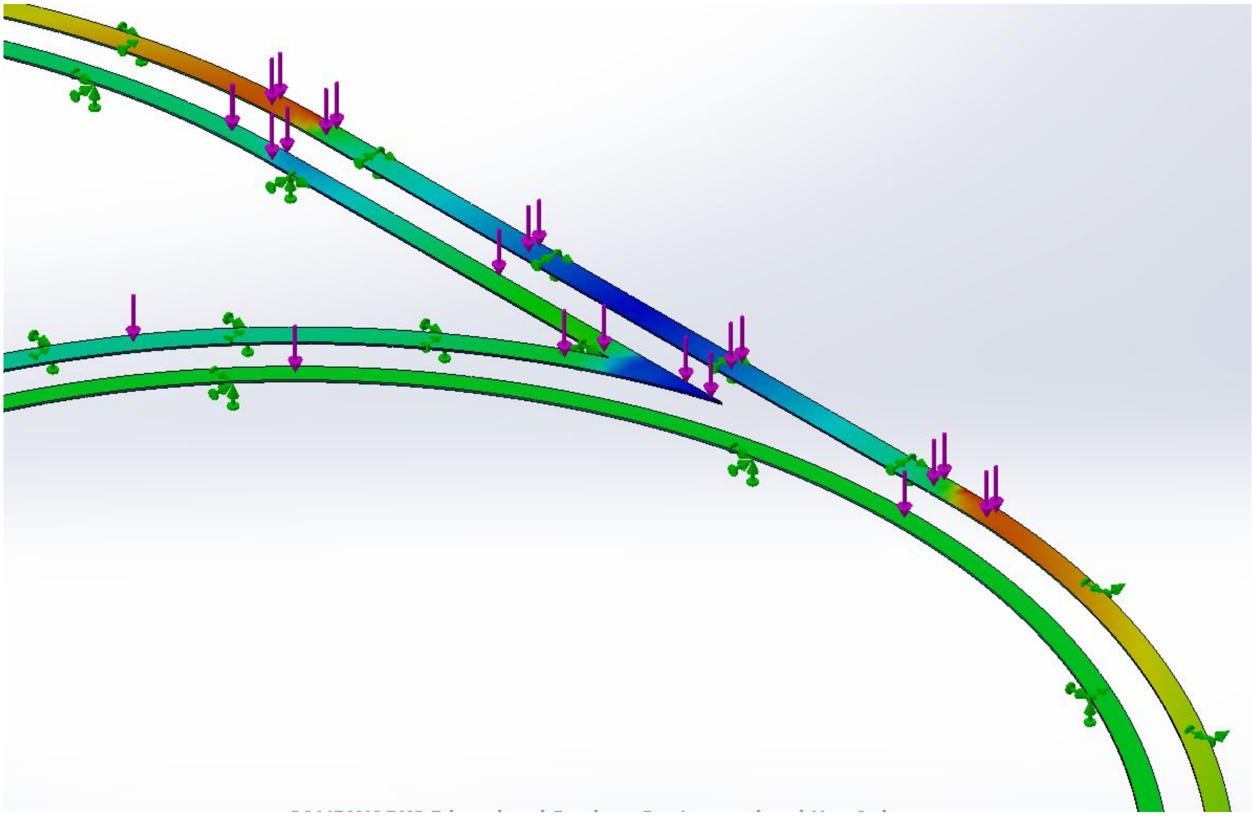


Figure 26: Closeup of Former FEA Study

In previous FEA studies done on the track, the team has designed the study as shown above in Figures 25 and 26. This FEA study showed that the track deflected a maximum of 1.4mm, however this study was later proven to be providing false results. As seen in the former FEA study in Figure 25, the track assembly is featured at the bottom face, and the gravitational force is applied at the top face. However this FEA study is incorrectly designed, as the real life equivalent would be as if the track without any uprights was placed on the ground compressed against the ground. In actuality, the track would not be supported as such and will only have supports at specific points. Thus the reported deflection of 1.4mm is considered false, and the real deflection is greater than such. Another former FEA track deflection study was created with the uprights. However this study proved to have many errors, and would not run at all. This is the reason that an FEA with the entire track and all the uprights is not contained in this report.

Instead a simplified FEA as shown in Figure 27 and 28a was created with just a slice of the track between two of the uprights, and this study proved to be more beneficial. In addition to not having many errors, the new study configuration provided just as similarly accurate results and had reduced computing time.

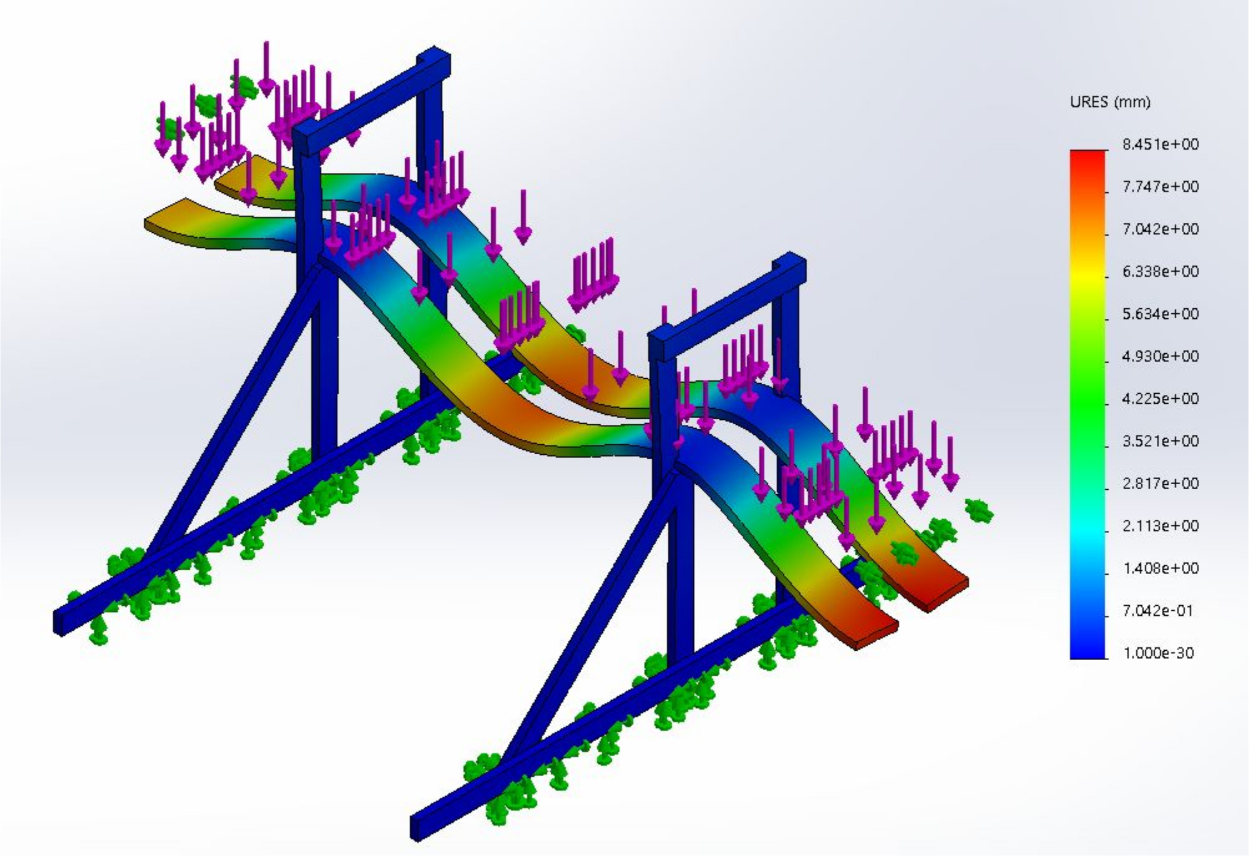


Figure 27: Simplified FEA of Straight Section (Max Defl: 8.541mm)

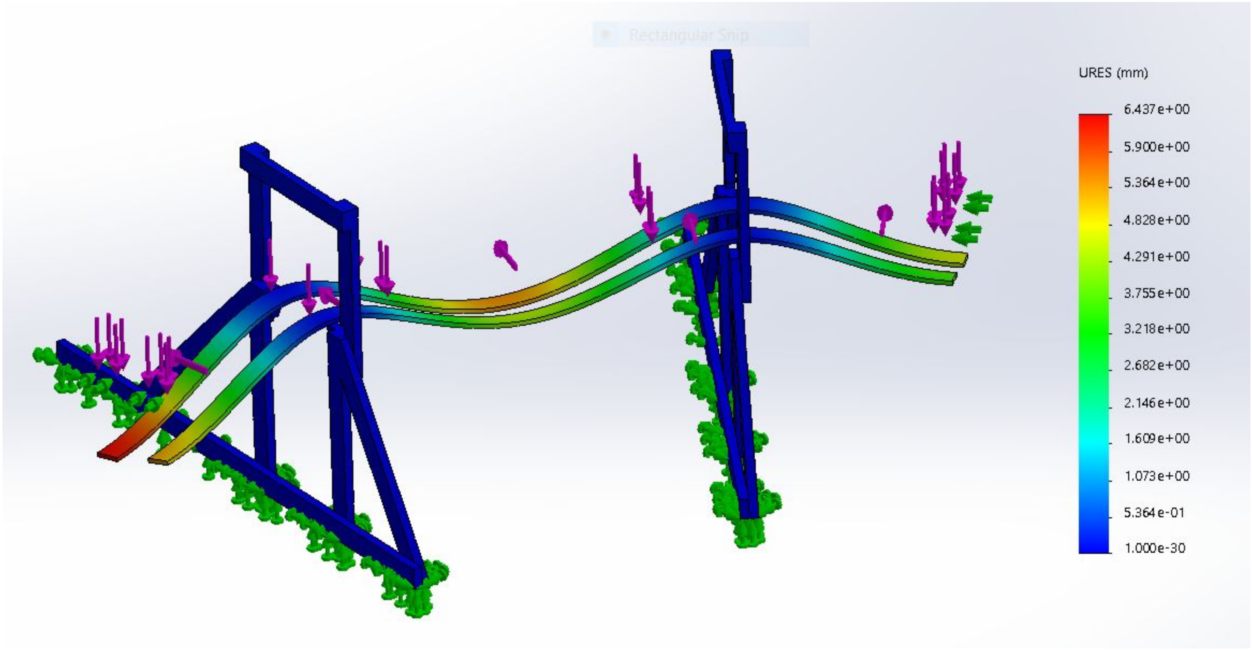


Figure 28a: Simplified FEA of Curved Section (Max Defl: 6.437mm)

There were two simplified FEA studies run on the track to give insight into track deflection. The studies were conducted by placing fixed supports on the bases of each upright as they would be bolted to the ground in real life, and the cutouts of the track were given roller supports as they were to be allowed to deflect up and down. The centripetal forces were placed on the external gap of the 160mm gap between the two track pieces, and the gravitational force was placed on top of the track. First of which was between two uprights on the curve, where the applied forces would be the centripetal force and gravitational force of the bogie. The second was between two uprights on the straight section of the track with just the gravitational force. The magnitude and derivation of both the gravitational and centripetal forces can be found in Figure 56 of the Appendix. The results for these studies can be found in Figures 27 and 28a. The resulting maximum track deflections for each of the studies respectively are as follows: 8.451mm and 6.437mm. As shown in Figure 22, all track deflections are less than the design goal of 10mm.

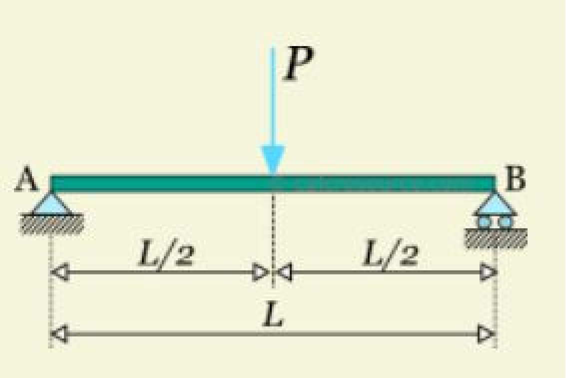


Figure 28b: Modelling of simply supported beam for deflection hand calculations

Hand calculations were done for verifying the FEA. This was modelled as a simply supported beam as shown in Figure 28b, where the supports were the uprights on both sides. Both calculations for the straight and curved sections can be found in Figures 56a and 56b of the appendix. Both calculations were within 5% of the FEA study deflections, thus verifying their results.

Switching Mechanism

In the beginning of this project a bogie was going to be provided to the team from Bill James at Jpods. Jpods, as mentioned earlier, is a company that focuses on a pod system of travel just as Spartan Superway. Unfortunately, some unforeseen circumstances in regards to the COVID-19 pandemic did not allow for this collaboration to take place. As a result, the team decided to use the CAD from Bill James for the bogie design, but create a unique switching mechanism. This switching mechanism still has some fine details to be worked out, but it should work just fine on paper, and through the Solidoworks animations the team did.

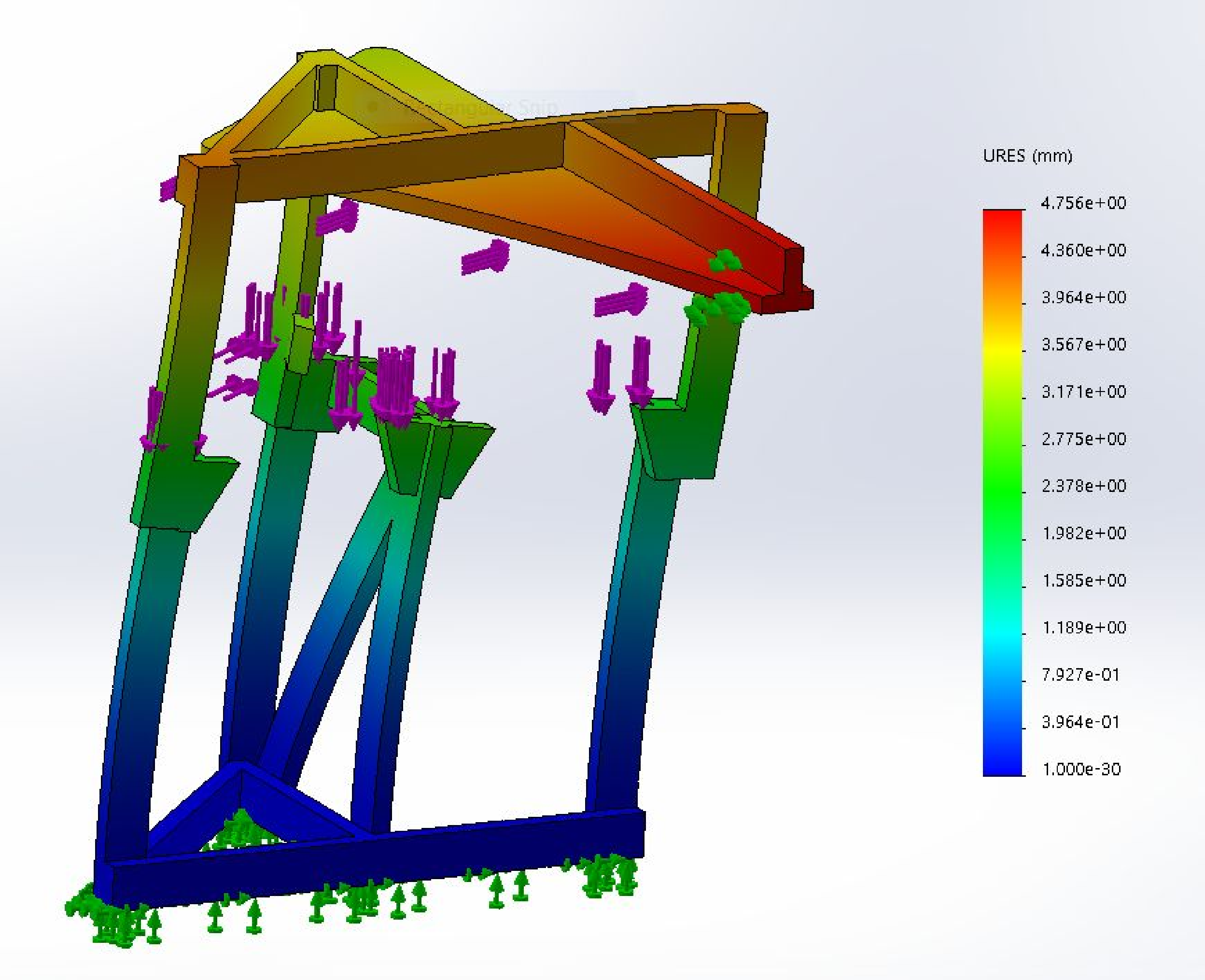


Figure 29: FEA of Upright with Switching Mechanism on Curved Portion (Max Defl: 4.756mm)

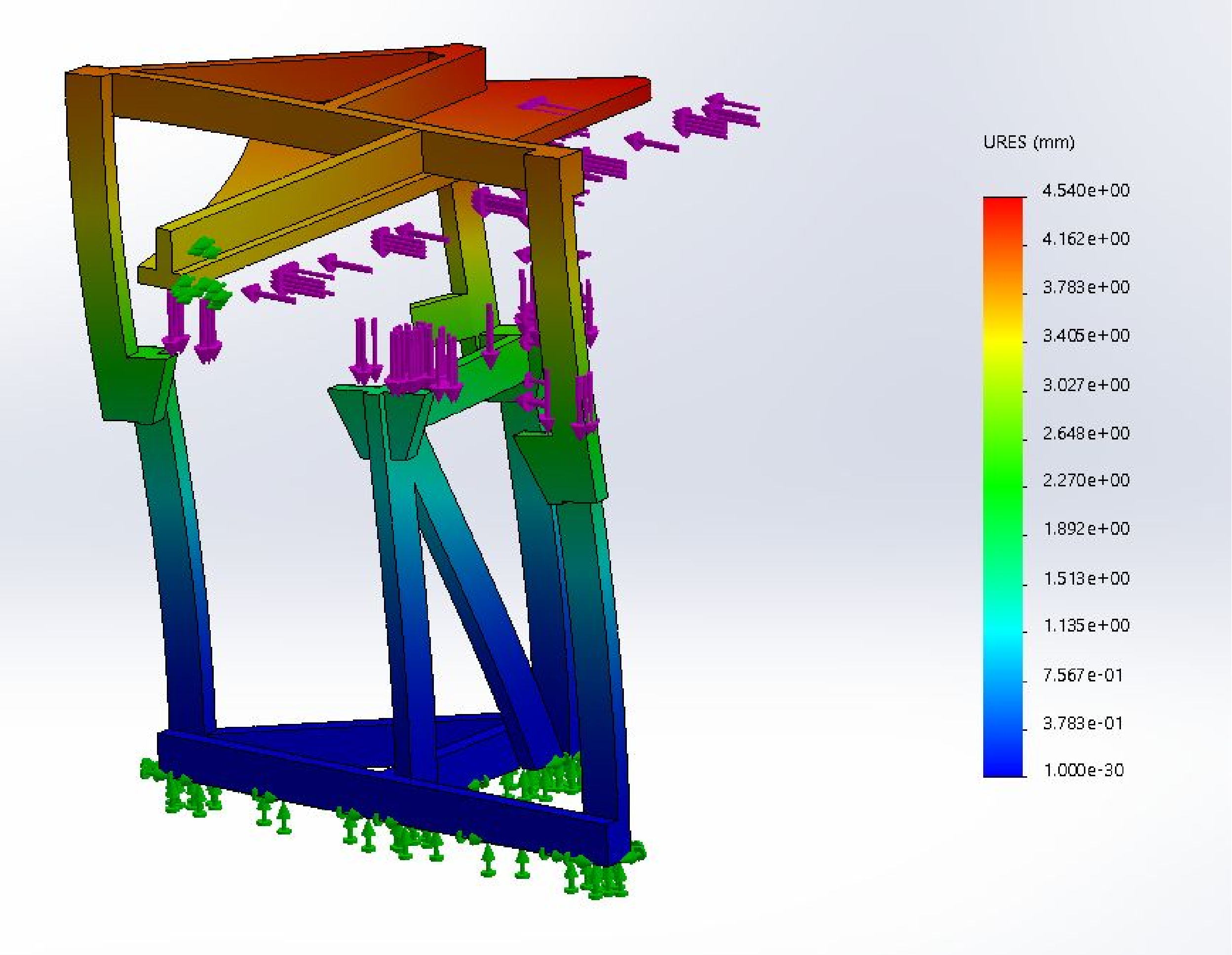


Figure 30: FEA of Upright with Switching Mechanism on Straight Portion (Max Defl: 4.540mm)

Two FEA studies were run on the upright with the switching mechanism that the bogie would lean on in Figure 29 and 30. The upper triangular piece was supported in the air by two uprights. The other upright is not pictured in the figures 29 and 30 as it was not needed for the analysis, since its effect on the FEA deflection was considered negligible. Essentially the FEA study was conducted by fixing the base of the switch upright in place, then a roller support was placed at the cut of the triangular piece. The centripetal and gravitational forces were placed downwards on the upright where the track would sit, and the centripetal forces were placed on the curved and straight part of the Y-junction as well as the section of the upright where the track would touch the upright. Both the resulting deflections for the straight and curved Y-junction were 4.540mm and 4.756 respectively.

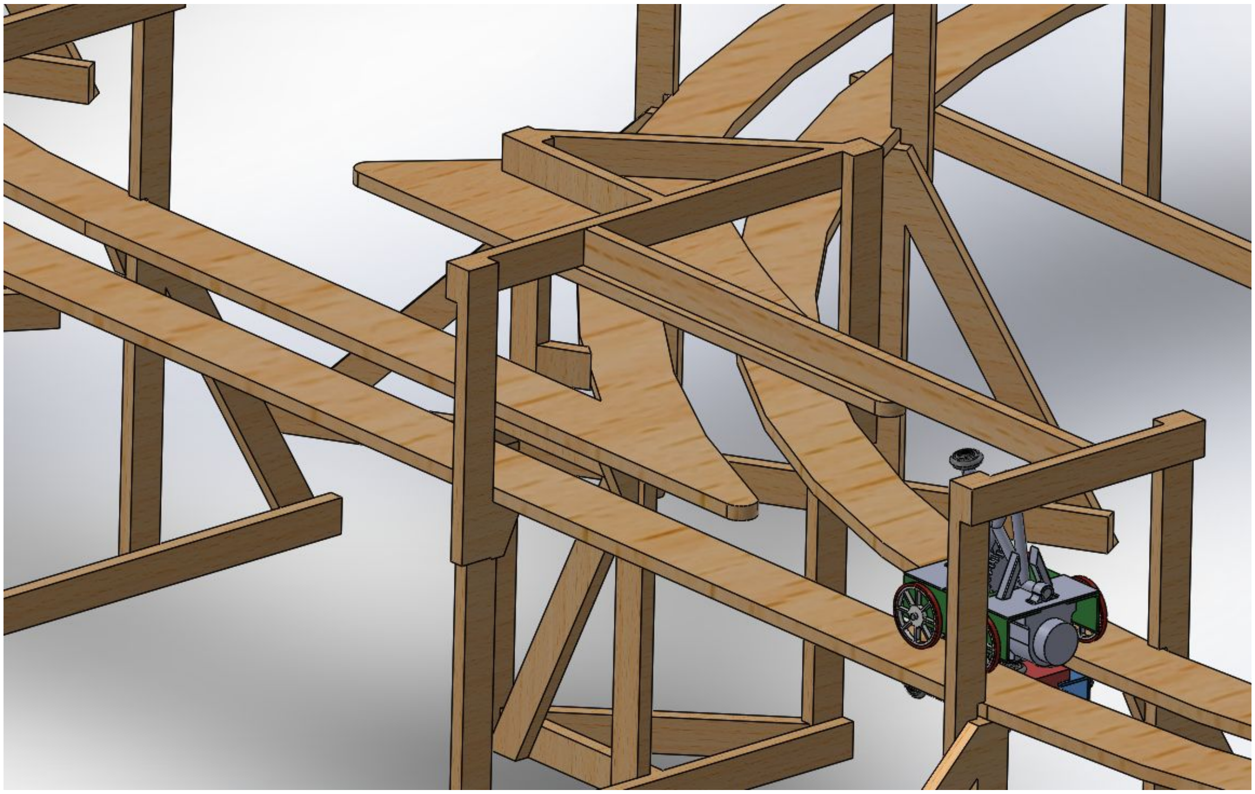


Figure 31: Visualization of Bogie traversing Y-junction at straight section (Before)

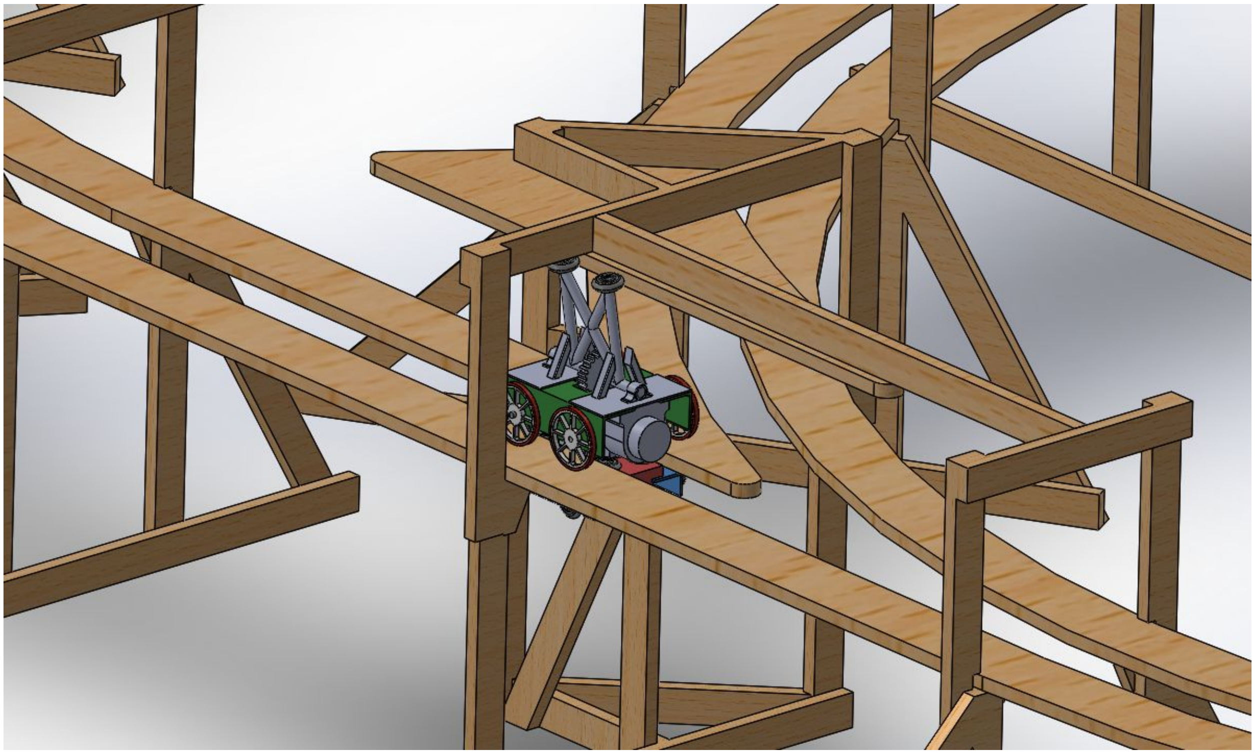


Figure 32: Visualization of Bogie traversing Y-junction at straight section (During)

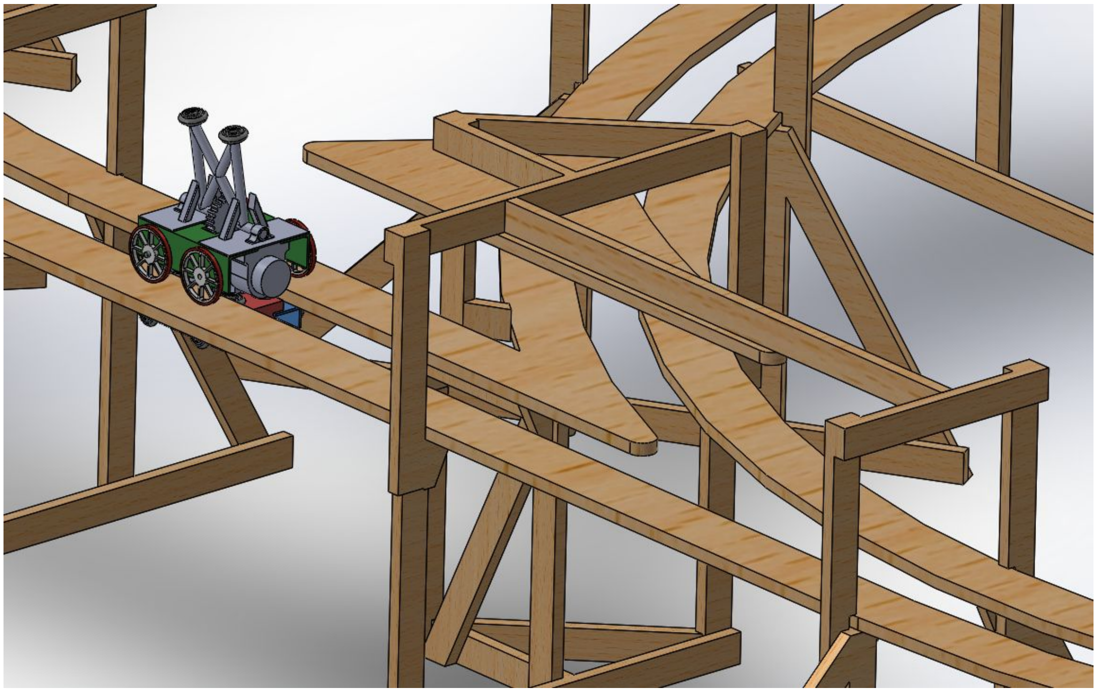


Figure 33: Visualization of Bogie traversing Y-junction at straight section (After)

The traversal of the bogie before, during, and after can be seen in Figures 31, 32, and 33 respectively. As the bogie travels through the junction there will be a point at which one side of the wheels of the bogie will not be contacting the track. This will result in an unstable situation for the bogie as it will be in mid air balancing on two wheels on one side. To remedy this problem an upper triangular member at the top will be contacting the bogie's switching wheels to allow the bogie to resist that moment to flip over when traversing the Y-junction. Similarly, the traversal of the bogie before, during, and after can be seen in figures 34, 35, and 36. This junction works the same way as the straight by utilizing the upper triangular member to lean on the bogie.

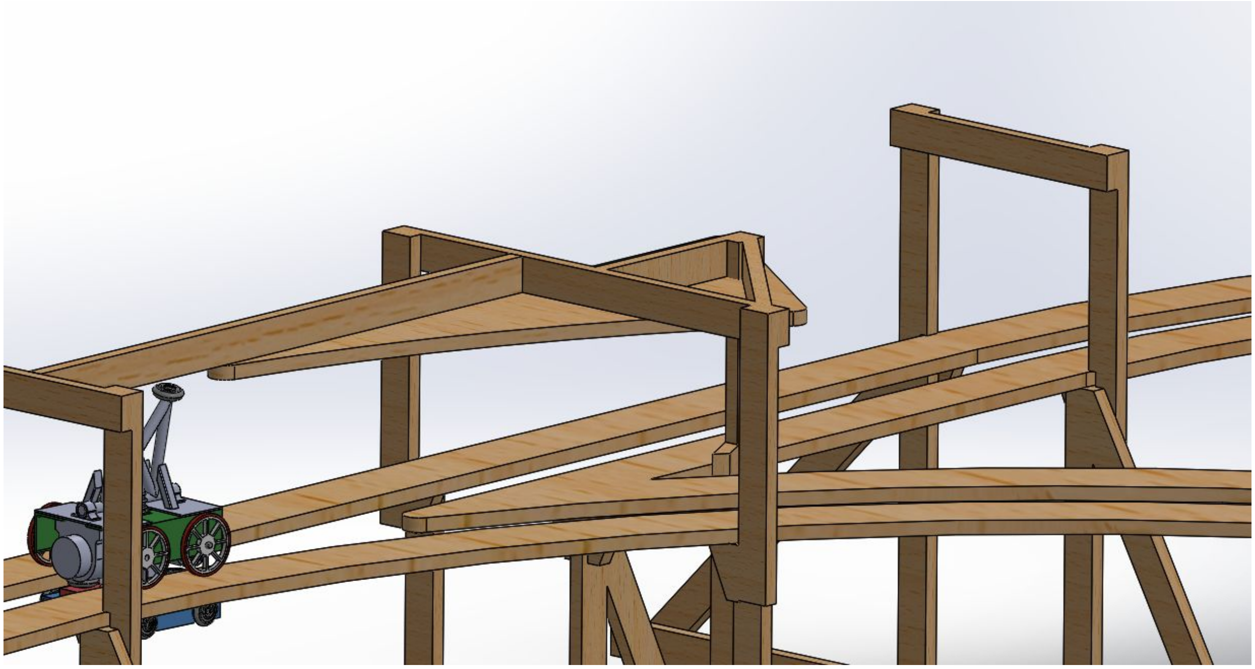


Figure 34: Visualization of Bogie traversing Y-junction at curved section (Before)

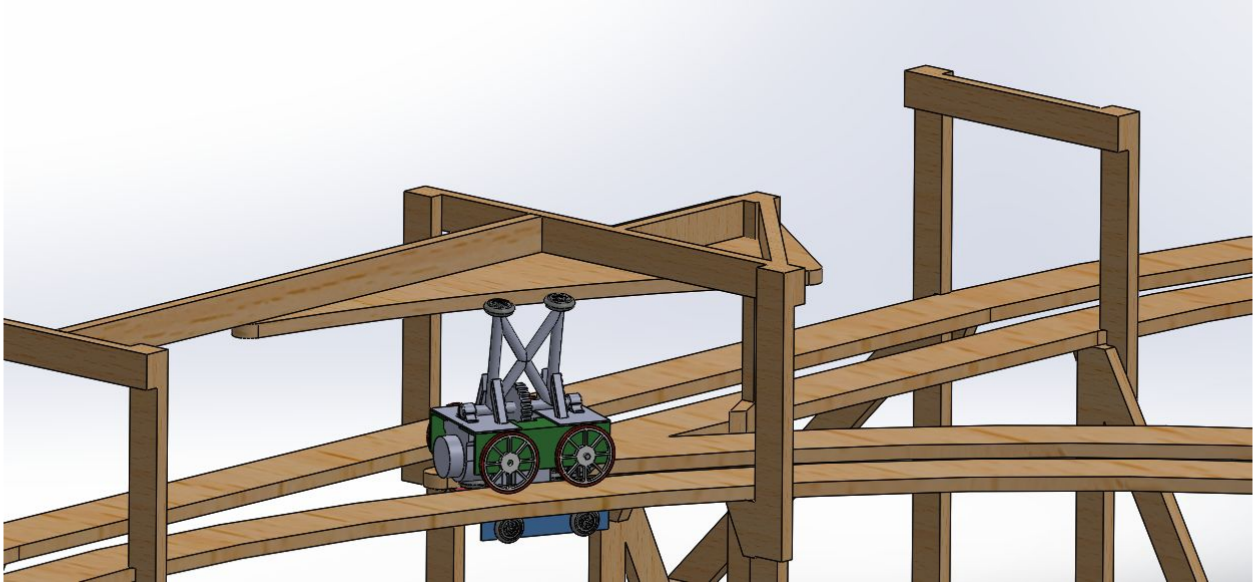


Figure 35: Visualization of Bogie traversing Y-junction at curved section (During)

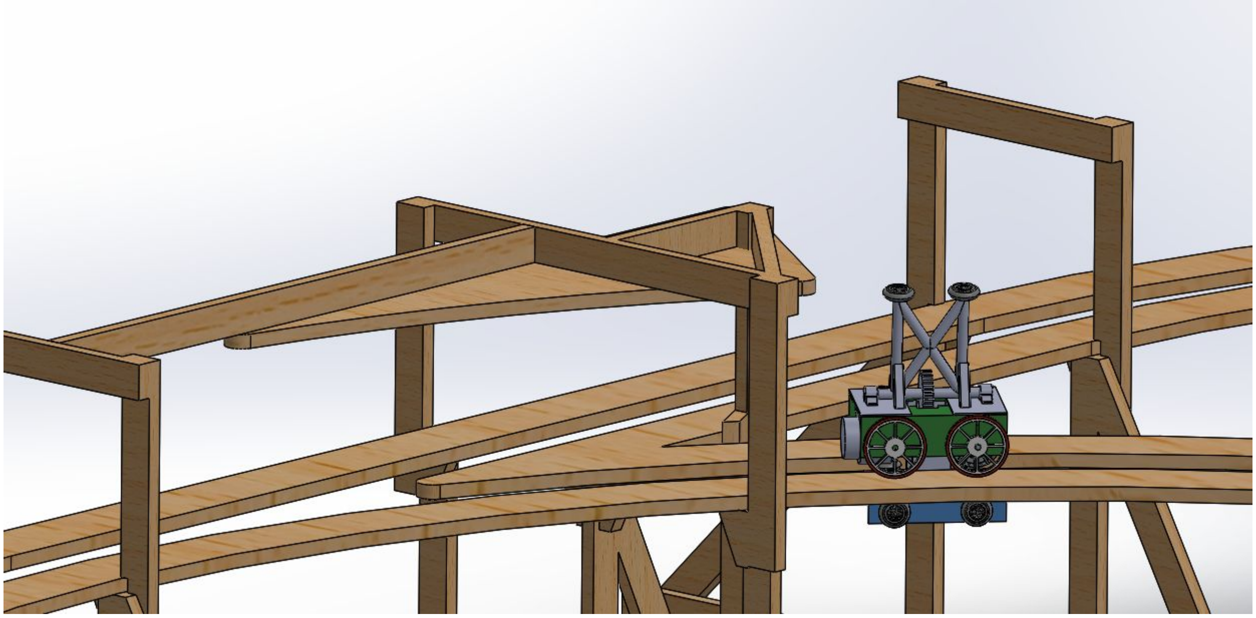


Figure 36: Visualization of Bogie traversing Y-junction at curved section (After)

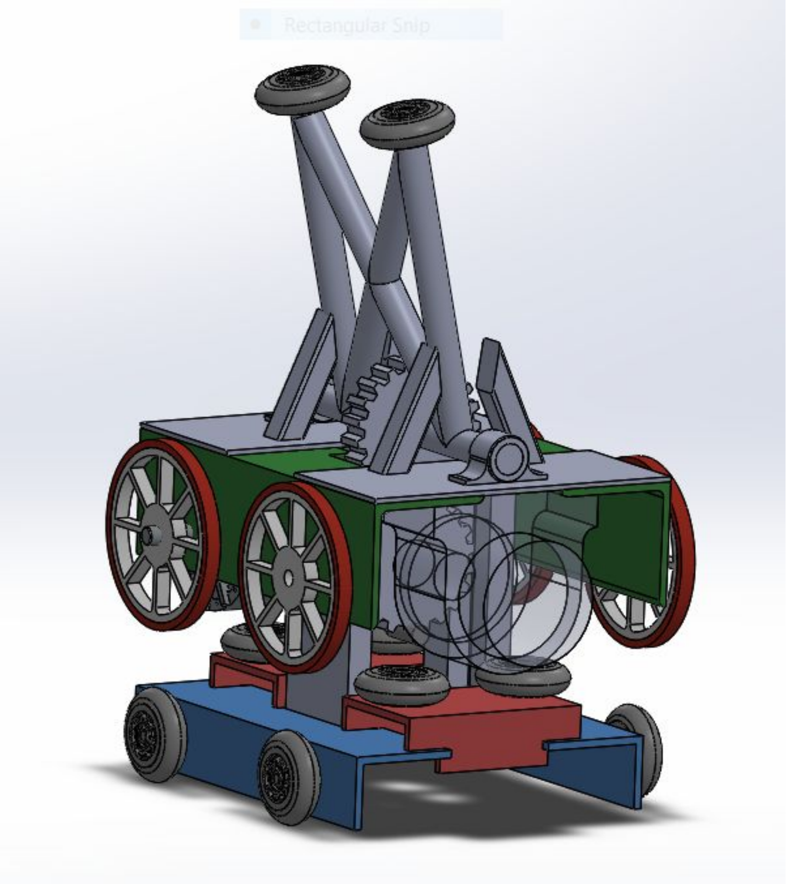


Figure 37: Visualization of Bogie's Switching Arm at straight section

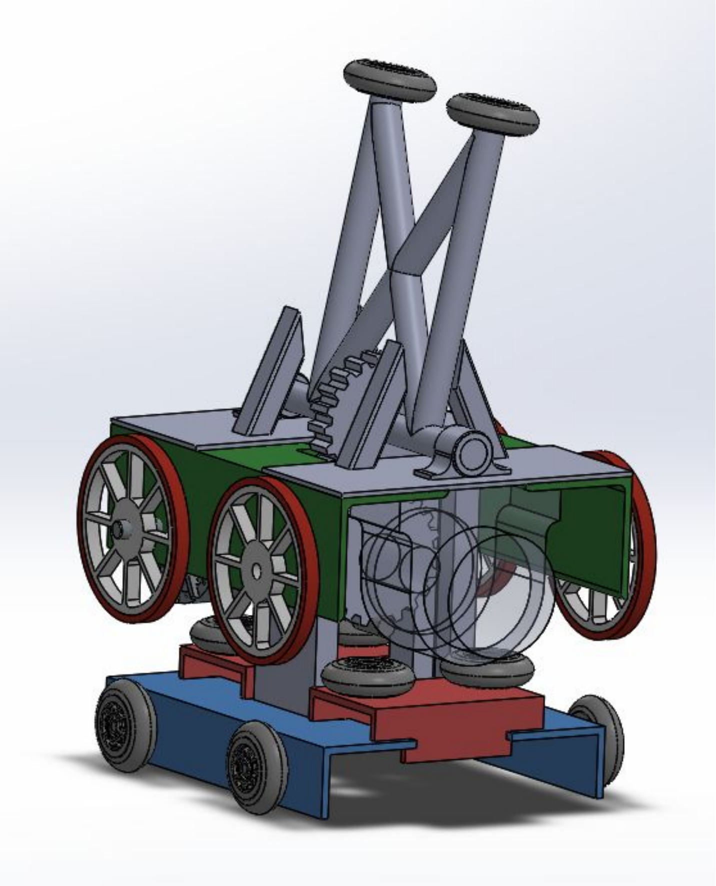


Figure 38: Visualization of Bogie's Switching Arm at curved section

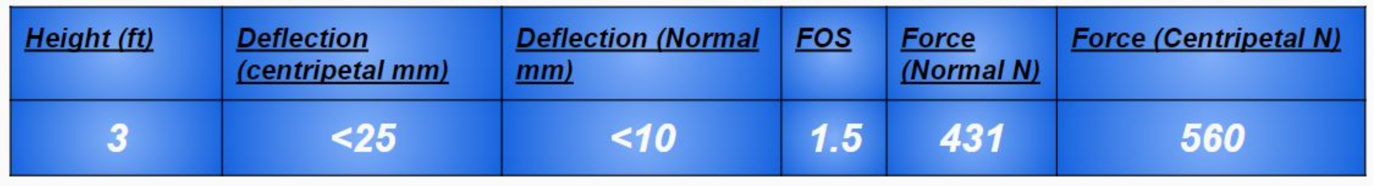
The bogie switching mechanism consists of a switching arm with two wheels to ride on the Y-junction. Figures 37 and 38 show the two orientations of the switching arm when at the junction. The arm consists of two wheels connected to a metal tubing that has bearings to allow the wheels to spin. The arm rotates about the pillow block bearings that mount the arm onto the bogie. The actuation of the arm is limited by four switching arm stops, that allow the moment of the bogie to be resisted by the arms stops rather than the power of the motor. The switching arm has a gear on it that connects to the driven gear of the motor mounted within the bogie. The motor is transparent to give a better view of the internals. Lastly, 3 sets of wheels can be found on the bogie. The red wheels are the ones that traverse on top of the track, the grey ones below the red wheels mount onto the bottom of the track, and the grey sideways wheels mount onto the 160mm gap between the external and internal portions of the track. The sideways wheels have spring supports to allow for a little tolerance in the manufactured 160mm gap.

Overall, the switching mechanism has some real promise, and if the design is executed properly, it should work really well. The FEA results that were done were primarily focused on proving that the Y-junction piece would be able to handle the moment imparted from the switching mechanism wheels. In addition, the team would like to point out that in order to finish the switching mechanism, a motor will need to be mounted to the bogie to control the gear, and some code will need to be written to move the motor.

Upright Design

The uprights for the project are an important consideration because if the design is poor, the track could fall down or break under load. The track needs to be well supported, and all the forces need to be properly accounted for or the main goal of the track being a testing platform will not be fulfilled . The different iterations of the uprights and why the team thought certain designs had promise will be discussed in fine detail, this bit focuses on what the actual design specifications are. To start, the upright needs to be capable of supporting the weight of the track plus a bogie traveling at speed. Specifically, the upright needs to support a static force from the track of 40 kg. Please see appendix Figure for calculation on forces. In addition, the track needs to. All of these loads need to be supported with less than 25 mm of deflection in the centripetal direction and 10mm of deflection in the normal direction.

If the upright cannot support the weight of the track plus bogie traveling at speed, then it is incapable of fulfilling its primary purpose. Next, the upright design needs to allow for the team to study the bogie to track interaction from above and below. In other words, this track is meant to be a testing tool, and in order for the team to successfully test the bogie and track, the team must be able to observe the track from the top, hence it cannot be tall, but also, observe the track from the ground, so it cannot be too short. When we talk about the tracking being too tall, what is meant is, that the track cannot be something where someone needs a ladder to observe the bogie. More specifically, if the track is 5 ft tall that would be considered too tall. As a result, the upright must support the track 3 ft off the ground in order to be the best height for observation.



Height (ft)	Deflection (centripetal mm)	Deflection (Normal mm)	FOS	Force (Normal N)	Force (Centripetal N)
3	<25	<10	1.5	431	560

Figure 39: Table illustrates the design specifications for the upright

Previous Upright Designs

In this section the team expects to discuss some previous designs that were considered, and why the design was eventually rejected.

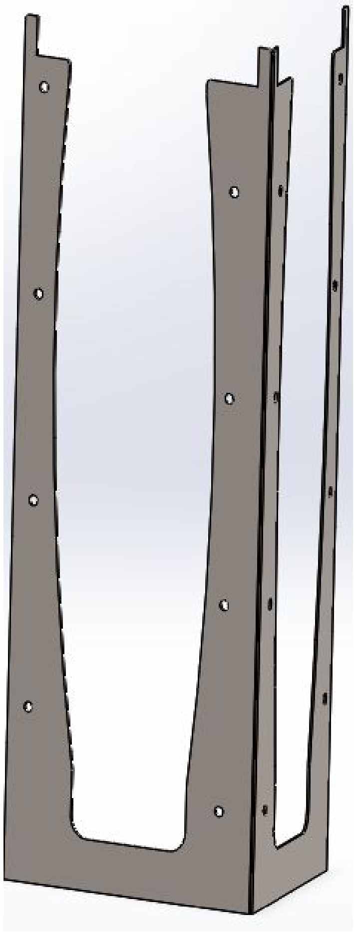
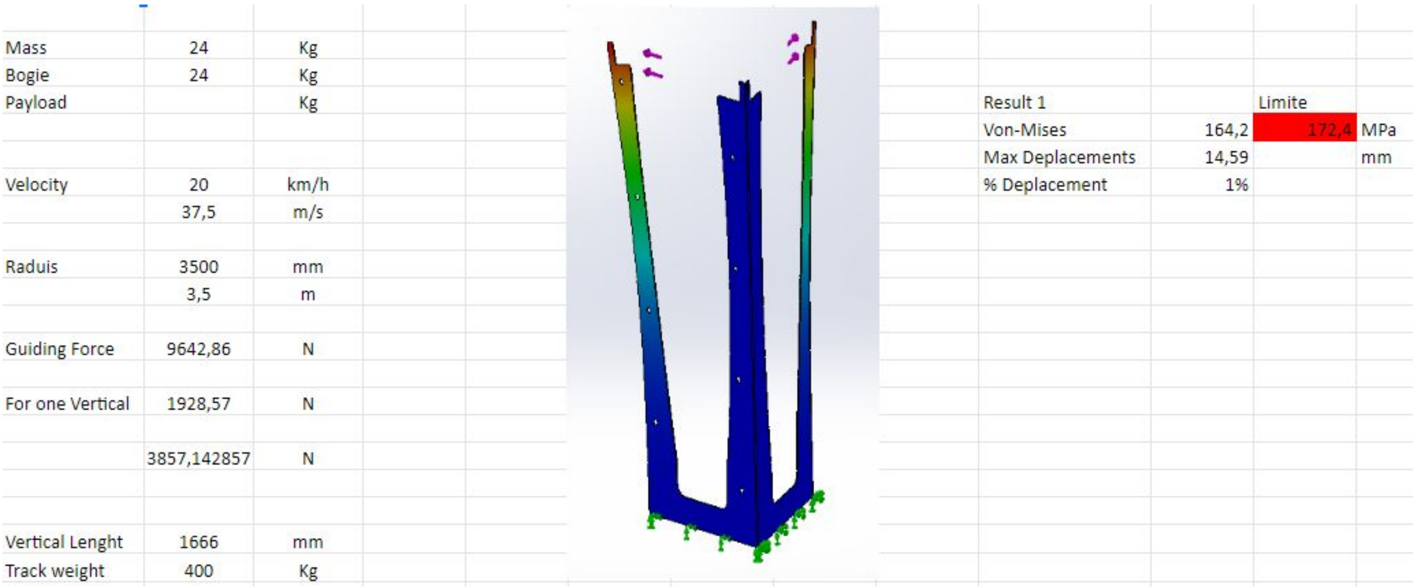


Figure 40: Upright design #1 as suggested by Jacques-Hariel

The first design that will be discussed is shown above, and was originally conceived by Jacques-Hariel over the summer. This upright design would support the track from underneath, and would be constructed from 20 gauge sheet metal. In this upright design the thought was fishing wire would hold together the upright, and as a result, the design would be strong and simple. To show its strength some FEA results are shown below.



Mass	24	Kg
Bogie	24	Kg
Payload		Kg
Velocity	20	km/h
	37,5	m/s
Raduis	3500	mm
	3,5	m
Guiding Force	9642,86	N
For one Vertical	1928,57	N
	3857,142857	N
Vertical Lenght	1666	mm
Track weight	400	Kg

Result 1		Limite	
Von-Mises	164,2	172,4	MPa
Max Deplacements	14,59		mm
% Deplacement	1%		

Figure 41: FEA of first upright with results in excel workbook

These FEA models were done with a 24 kg bogie traveling at 6.7 m/s. In this FEA model, the displacement was 14.59 mm under load. The ideology behind this design was that it would be easier and cheaper to manufacture. The final cost for all materials would be $25 per an upright. After some consideration, this design was turned down by the team. One of the main reasons this was turned down was because it did not meet the team's design specifications. The team does not believe that this design will fail, but in the teams opinion there was a better design out there. In addition, this design seemed like a manufacturing nightmare. The fishing line that would be used to string the upright together seemed like it would be too complex, winding wire together is no easy task, and the right amount of tension, or the design would fail. Additionally, the sheet metal would be bent manually to achieve the proper shape. Some of the team members have experience with bending sheet metal, and getting any degree of precision out of manual bends is near impossible, plus bending sheet metal into that particular shape would be even more challenging as the base would be difficult to bend with the 3 other pieces sticking up as shown in the picture. Overall, this design proved to be too complex, expensive (compared with other designs), and not strong enough for the purposes of the Full Scale Team.

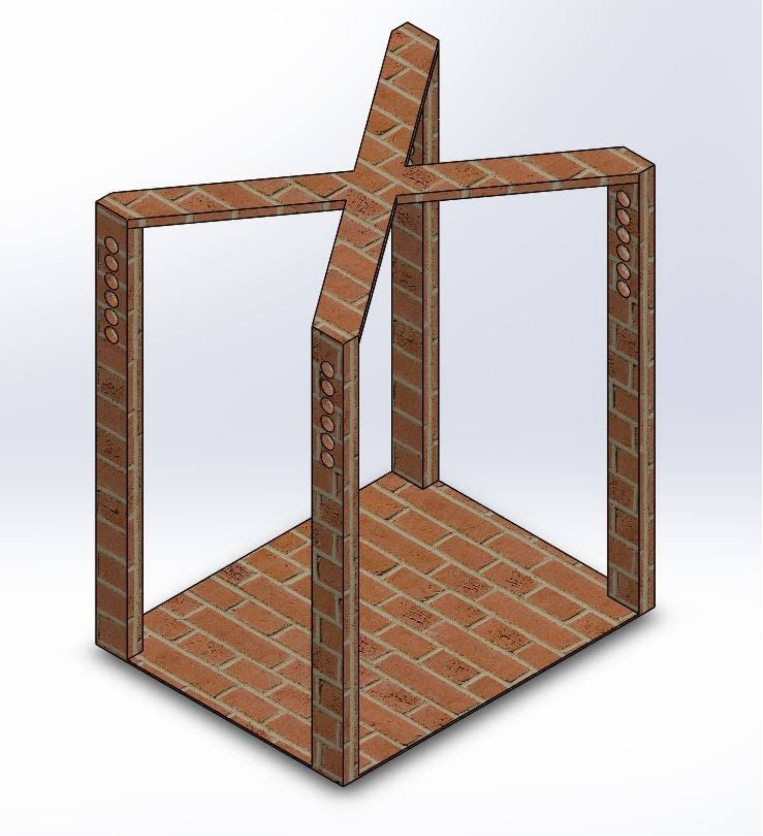


Figure 42: Second upright design consideration

Another, alternative design the team considered is pictured in Figure 42. Please note that the depicted upright is rendered in brick to help show some finer details of the upright, the actual design consisted of douglas fir wood. Moving on, this design was first conceived after taking a stroll around the Spartan Superway headquarters. When the team was walking around, the expectation was to find excess materials floating around, and then seeing if the team could make something work from there. After a stroll, the team noticed an abundance of douglas fir 2x4's. After requesting permission, the team collected the materials and was able to put together a tentative design. That design is shown above, and the thought process was that the upright the team had designed is going to be cheap to make, easy to manufacture, and sufficiently strong for the purposes of the 11m track.

However, after an extensive conversation with Professor Furman about this design the team decided against it. Before, the reasons for denial are discussed, the initial design will be explained. The premise for this design was for the track to lay on dowels (clothes hanging dowels), and these dowels would have different holes they could fit into, as a result if the ground was not level or if there was an elevation change in the ground this would not affect the track itself and the bogie would simply travel through the middle of the upright. In addition, because of the adjustment capability of the uprights, the uprights could be mounted anywhere without really affecting the track. In other words, the room for which the 11m track recides is a courtroom with different ground elevations, and if this upright design was utilized, then the upright could rest on the raised portion and still allow the track to remain level. However, while this and a couple other features made this design great at first, Professor Furman quickly brought some important flaws in the design. For example, since this upright is designed to be modular and used on straights and turns, the upright has no cross bracing at the base, hence the centripetal force of 560 N would push the upright over. This is something that Professor Furman immediately brought to the team's attention. Furthermore, Professor Furman also mentioned that the holes are a good idea, but the bogie cannot actually travel through the dowels if they go through both holes. This was a massive flaw in the design, so within one class session this idea was quickly scrapped for a better, more improved design, the final design.

Previous upright design

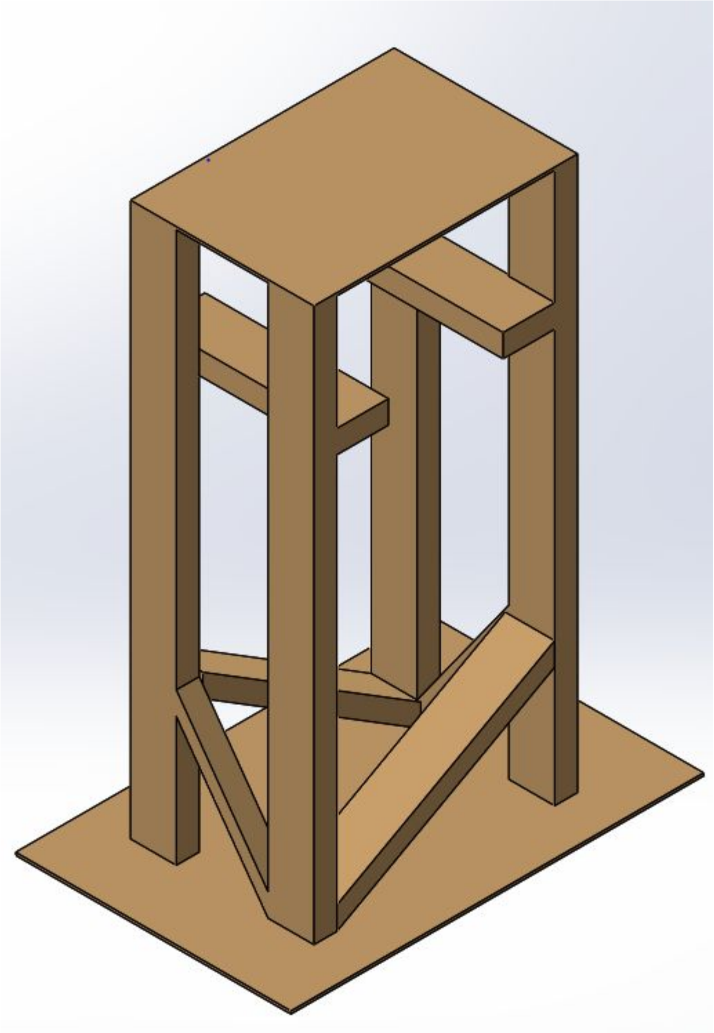


Figure 43: Previous upright design

Pictured above is another alternate design for the upright. This design was checked To reiterate, the design goals for the upright are too: support a 560 N centripetal load, 400 N static load, handle bogie traveling at 6.7 m/s, be 0.91 m above the ground (3 ft), have a FOS of 2, and all of these conditions must be met while deflecting less than 25mm. Now, this upright design works by having the track lay on the protruding pieces of 2x4 wood. Since the protruding piece (the ledge as the team calls it), has some thickness to it it allows the track to be screwed to the ledge. In addition, the bogie will not get stuck on the track because there is space in the middle for the bogie to travel in, unlike the previous design. Furthermore, since the supports at the bottom of the track oppose each other, the upright will not twist under load. The base of the track is purposely wider than the base because there are many square pieces of that size not in use, so this will help out with reducing cost. After each nut and bolt is accounted for, the final cost for this upright is $12. This $12 dollar cost is about half the cost of the first upright design. It is important to note that the $12 cost assumes everything is purchased out of pocket and not found in the Spartan Superway headquarters.

Previous Upright Analysis

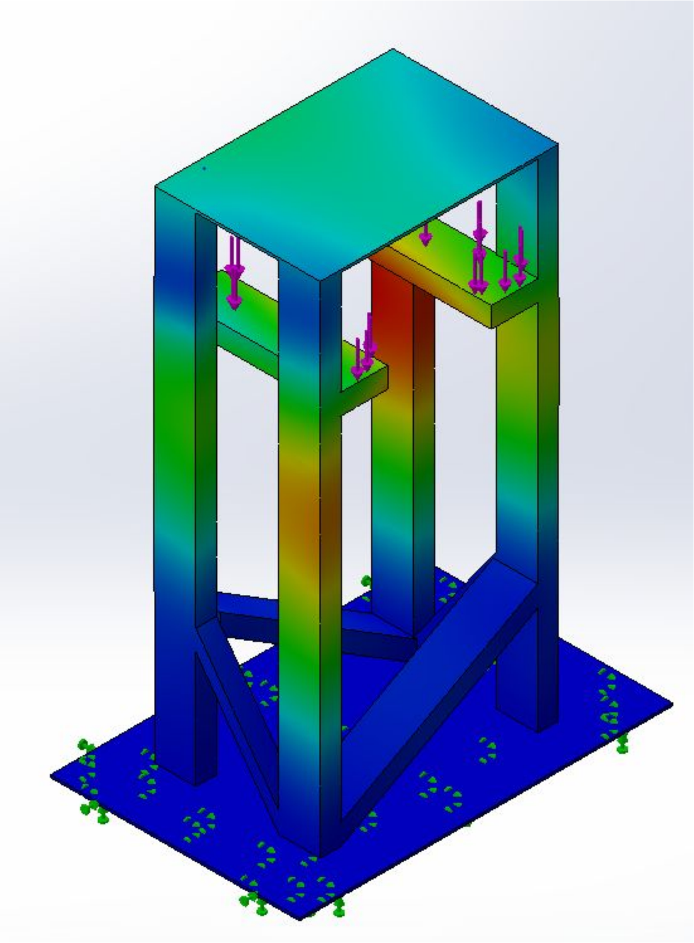


Figure 44: FEA of upright in static loading

In order to actually prove that the uprights would meet the team's stringent requirements, a proper FEA model is needed (pictured above). Briefly, an FEA model is only as good as the input, an oftentimes coined phrase is "garbage in, garbage out," so it is important to discuss the way the model was constrained, and the way forces were applied. For this instance, since static loading is being considered, the base is fixed to the ground, this is to say that essentially the base plate and the ground are one unit. In real life the base plate will be concrete drilled to the floor, so it is safe to say that the ground and the base plate are one. Next, the force is applied directly to the ledge pieces as the track, and it is at that point that the simulation shows 3 mm of deflection. With the 5 mm goal, the FOS can be calculated to be roughly 2. Now, in this simulation the force was applied over the entire ledge and this would be correct and true for the straight sections of the track, but this is not true for the curved sections. In the FEA model, when the forces are applied it is difficult to apply a force to only one miniscule area of an entire ledge, so as a result, the team made an executive decision to not try and simulate the curved sections, but rather add two 2x4's on each side to triangulate the uprights.

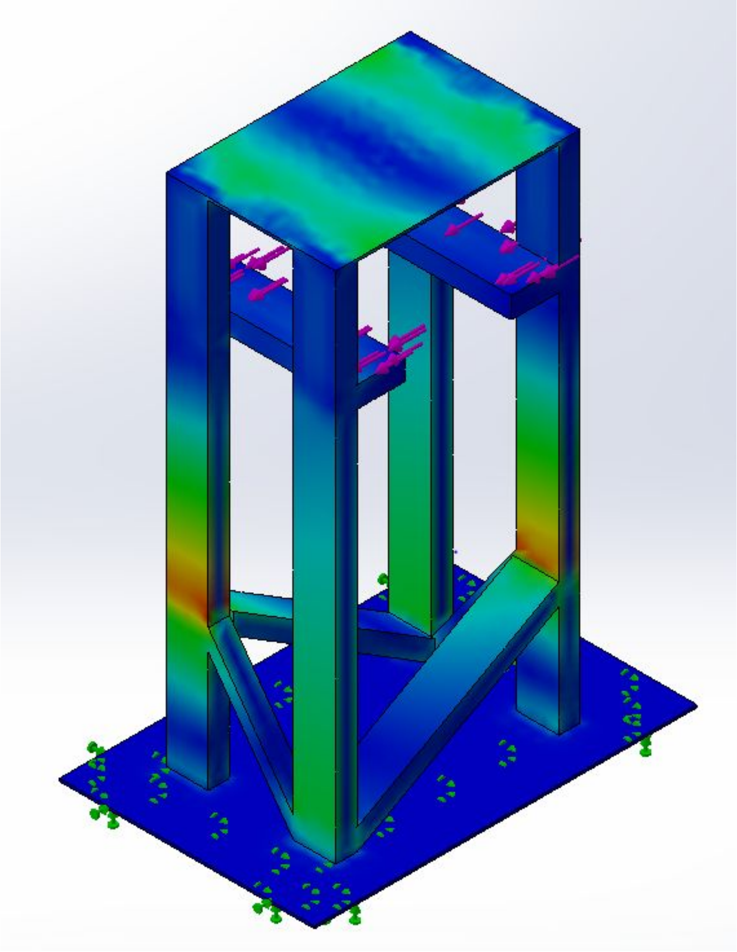


Figure 45: FEA of upright reacting to centripetal forces

Perhaps, the hardest simulation to run was for the centripetal forces. However, before the forces are discussed the upright was constrained exactly the same as the static loading model done previously. The base and ground were considered one unit, hence being fixed. Next, the force of 460 N was applied to the side of the upright against the main 2x4 beams. In other words, the centripetal forces will be pushing outwards in the same direction. It is important to note that the forces are pushing more against the side primary beams than pushing downwards. Since, this upright is for a curved section, most of the force will be pushing against the side, so as a result of that ideology, the force in the FEA model was set to be pushing against the primary beam. In the end, the upright deflected 3.3 mm in the centripetal direction. This 3.3 mm deflection was in the outboard direction, and is different compared with the previous static direction. Lastly, it is important to notice the high stress colors of the upright when facing centripetal forces. Most specifically, earlier in the report it was mentioned that the cross bracing was there to resist torsion, in FEA model it is clear to see that the design works really well because it reduces torsion in the high stress areas, however torsion is not the enemy of the upright, resisting the moment from the centripetal force imparted by the bogie is the main concern for the upright (plus of course holding the track up).

Overall the design for the upright successfully fulfilled the design goals that the team set in place. The analysis the team did through Solidworks Simulation proved to be beneficial, and it solidified the teams design, but there are some questions left about the design that need answering, and ultimately proves to be the end of this upright. The overall design is sound and will be functional in its current form, but in the end it was decided to not proceed forward with this design. The resistance to the centripetal forces, and the comlex manufacturing proved to be the end of this upright.

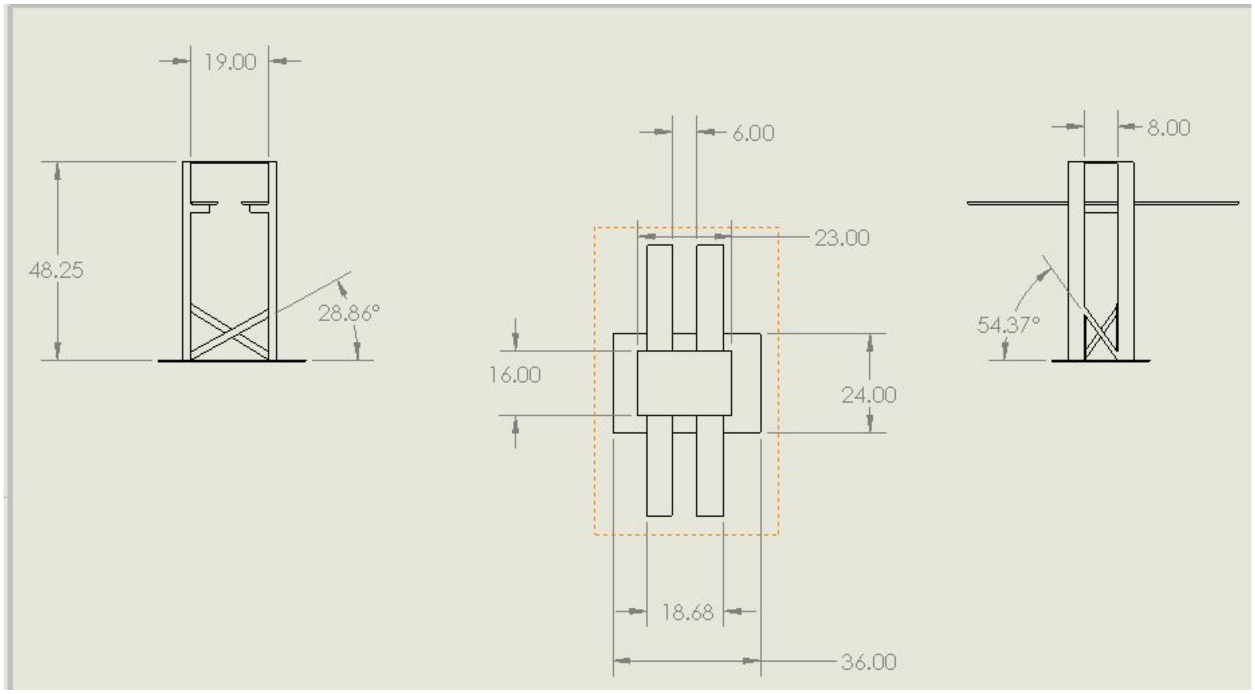


Figure 46: 2D drawing up of previous upright with straight track piece on top of ledge

The last step for the uprights is a final, highly detailed plan for manufacturing. In this figure above, the precise cut and angle for each piece is highlighted. In a test fabrication run (testing out ideal tools for certain manufacturing tasks), things like bandsaws, miter saws, and even hand saws were tested to see what would be the most ideal, and it turned out that using a hand saw turned out to be the easiest method. The primary reason the hand saw was better is because whenever power saws were used the wood would naturally heat up to the point of smoking, and that would leave a terrible smell in the room where the project resides. Many alternatives do exist, such as using a different blade and such, but ultimately, the hand saw is the easiest and "cleanest" method of cutting the wood. This decision can change for the future, but for now the team is sticking with hand saws.

In regards to materials, the douglas fir 2x4 beams are stored all around Spartan Superway headquarters, recently, the team walked around and collected a sufficient amount for the uprights, so at this point the primary material is sorted. In addition, the hardware envisioned to fix the upright together is #6 2 ½" wood screws. The reason for using this specific size is based on a recommendation from the Familyhandyman. In addition, wood screws are about $31 dollars for a pack of 500 versus $29 for the equivalent drywall screws (Home Depot). On paper a $2 dollar difference is not much for what is arguably a better product, however, after some research on from the FamilyHandyman, they report that although drywall screws might be cheaper and more readily available, wood screws have a higher shear stress resistance and since the top portion of the screw is not threaded, they are less likely to split the wood.

Final Upright

After some additional consideration the upright design was modified one last time. This new design was conceived because the old design raised some concerns about the centripetal force opposition. Ron Swenson told the team that the upright would be better if re-designed a little bit, so Ron was the source for this idea.

The new upright seen in Figure 47 is constructed completely out of 2x4 beams, and it utilizes #6 cabinet screws to hold it together. The new upright design will hold the track 3ft off the ground, and as the FEA analysis in the later paragraphs proves, will meet the required design specifications. Additionally, these uprights require very few angles to be cut as compared with the previous designs. In other words, the previous designs would require lateral support pieces to be cut at precise angles, and with the new design, the angles that need to be cut are rather simple, and the plunge saw would make quick easy work of it.

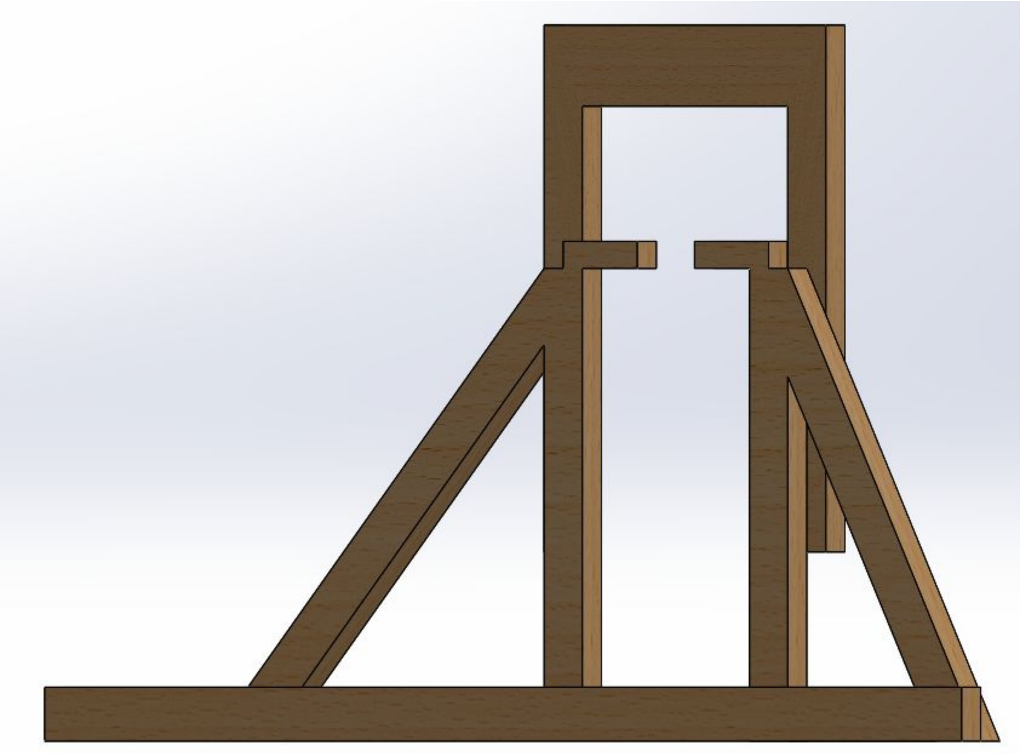


Figure 47: The final upright design

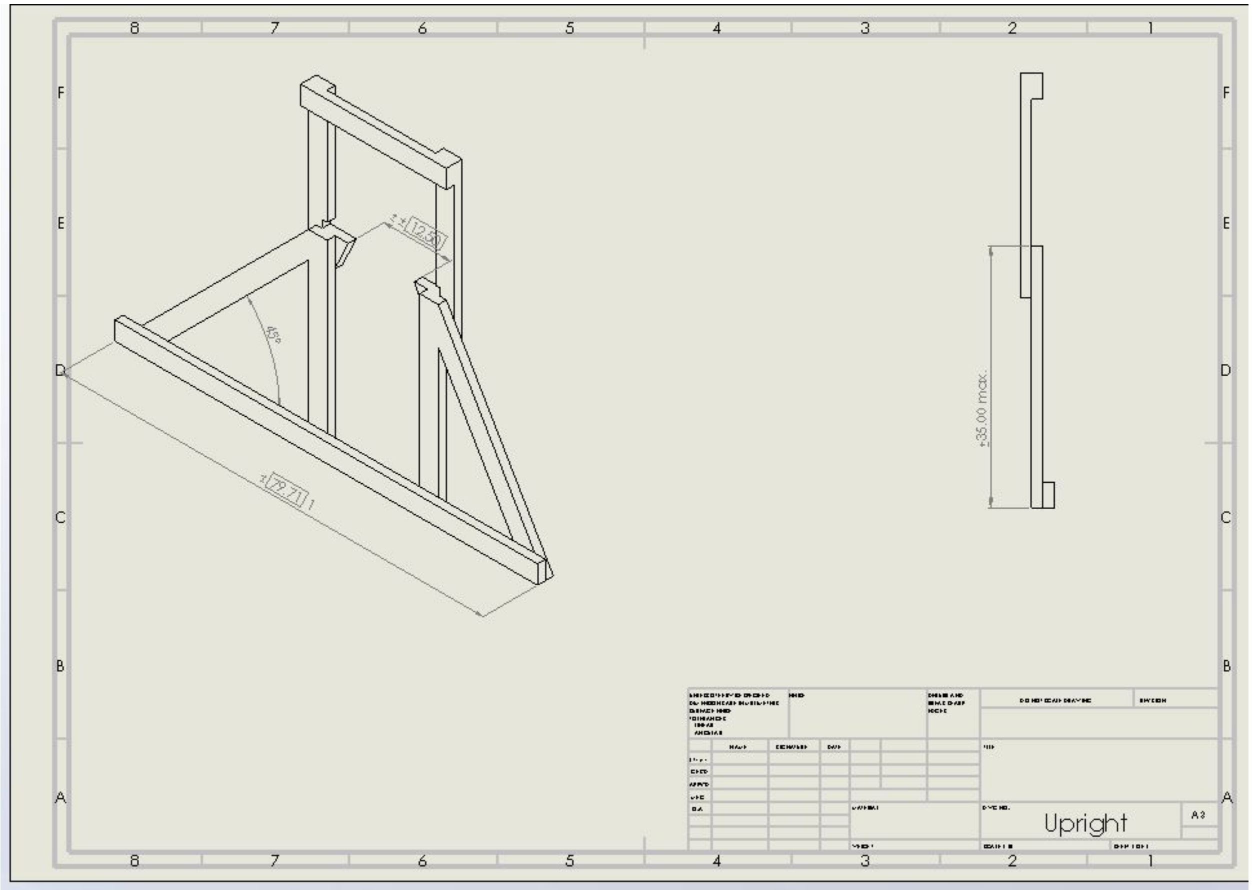


Figure 48: The 2D part drawings for the final upright

As seen in Figure 47, the new upright design uses a more triangulated design with a larger base. In addition, since that large base piece has been added in, it gives the upright a better chance to oppose the centripetal force. Since, the upright base is larger it gives the upright more surface area to oppose the centripetal force. The moment equation is $M = F * D$ where M is moment, F is force (centripetal force in this case), and D is the distance the force is from the pivot point. Since the elongated base is increasing the D value, the upright can oppose a higher centripetal force, this allows for the upright to deflect less with lower centripetal force. In other words, because the upright can tolerate a higher centripetal force, it deflects less with less force than the previous upright design.

In order to prove that the new upright design really meets the design specifications, a detailed FEA was run. The FEA was done in both the normal and centripetal directions. Figure 29 shows how we calculated the forces to use in the FEA analysis, and the bogie speed is set at 6.7 m/s. Figure 49 shows the constraints for the normal direction FEA analysis.

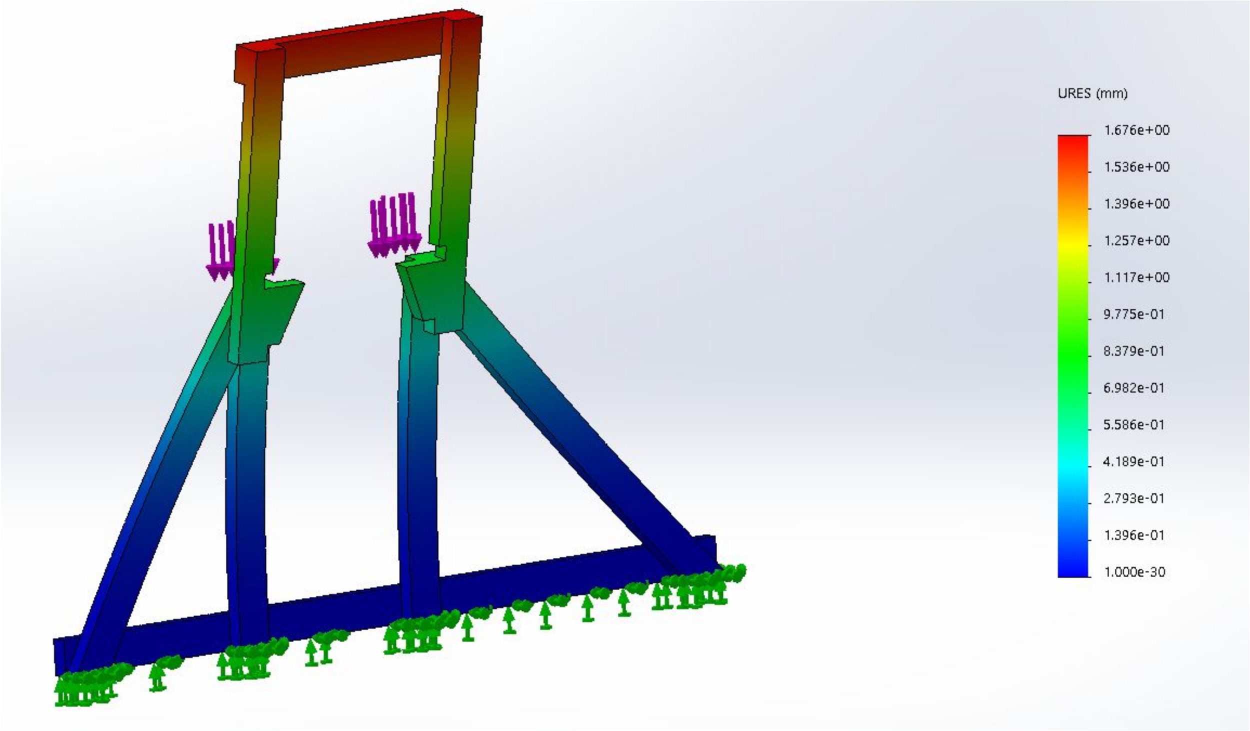


Figure 49: FEA in normal direction for upright

The FEA analysis shown here run on Solidworks Simulation fixes the bottom as shown in the green arrows, this essentially means the green in the ground pushing up on the base, and the purple arrows show where the force is applied. As a result, The new upright deflects 1.6mm in the normal direction which is an 51% improvement over the previous design which deflected 3.3

mm. The new upright design did improve over the old, but as mentioned previously the most important improvement is going to come in the centripetal direction.

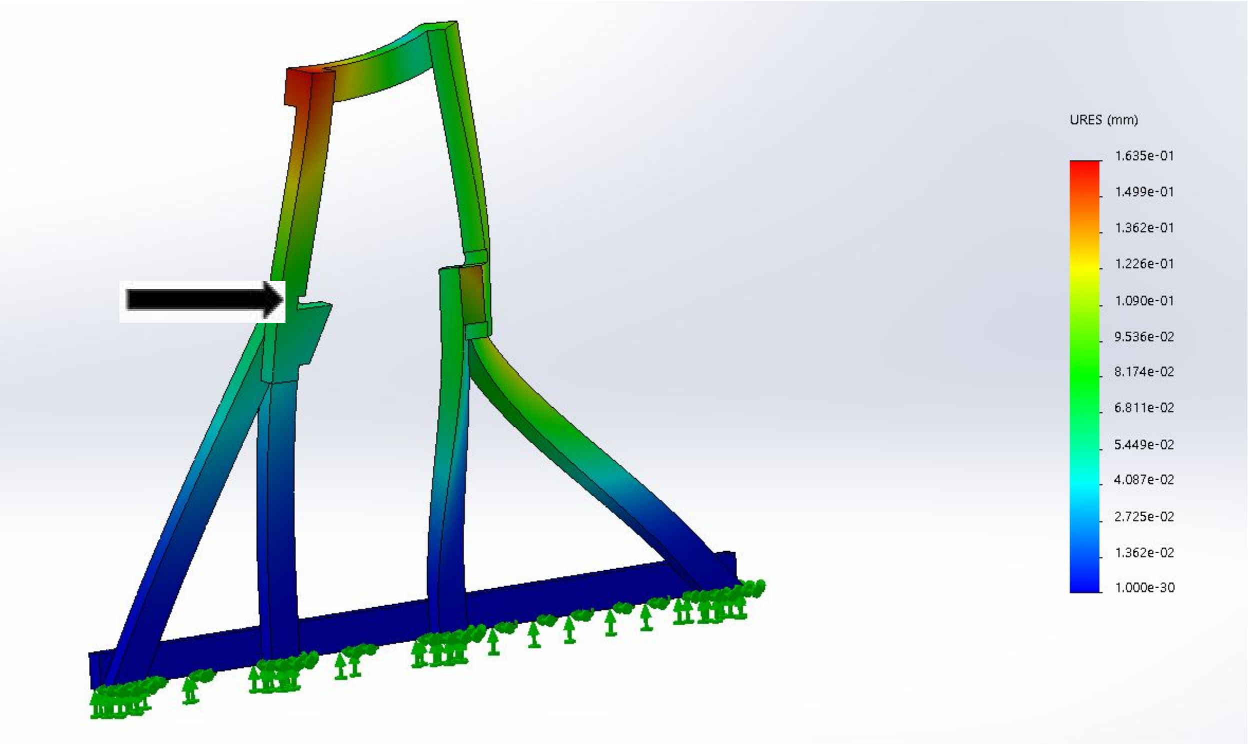


Figure 50: FEA in centripetal direction for upright

This FEA result shows the deflection in the centripetal direction. Again, the green arrows indicate the ground, and instead of purple arrows, one black arrow is shown, the black arrow is to indicate a notch in the upright for the track to slide in, and that arrow is to show that notch. The centripetal force was applied in that notch. FEA for new upright shows an 80% improvement over the previous upright in the centripetal direction because the old design deflected 3 mm whereas the new design deflects .16 mm in the centripetal direction. This low (practically zero) deflection met the design specifications by a long shot. The goal for the upright was to deflect less than 25 mm, and this design more than exceeds that. One other thing to mention, is at first this incredibly low deflection was suspect, so a group member actually physically stood on top of the track and walked across it, and the uprights did not appear to move at all. While this test is rudimentary at best, it somewhat proved that the design is working really well, and that the FEA is actually accurate because there was no visible deflection in the upright that the team observed.

The track has some junctions for a switch mechanism, and there are a total of 4 of these uprights throughout the track. Some analysis was done on these just to confirm they would still meet the design specifications that were set in place earlier. However, first the upright switch junction will be explained. Shown in Figure 51 is the upright for the switching portion of the track, the reason this upright needed to be different is because it is necessary for the switching mechanism to work. In addition, the upright here needs to be able to serve as a transition piece for the inner loop of the track. This track piece will see some centripetal load, but for the purpose of the FEA the assumption will be that it is 560 N as with the other FEA's. The reason 560 N is used is because 560 N is the calculated max, and this upswitched upright will not see anything more than the max. In addition, the normal force applied for the analysis will be 870 N.

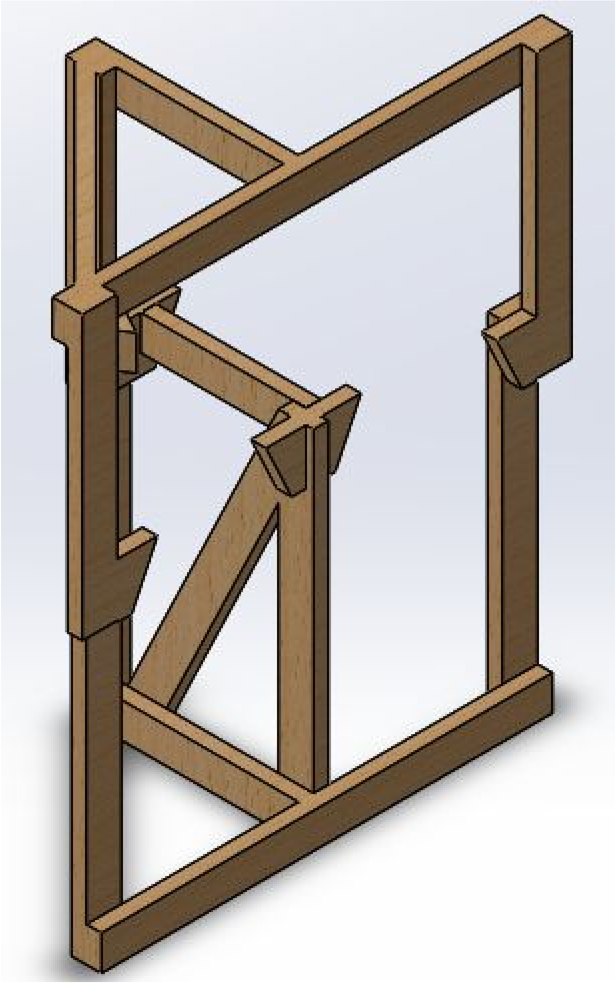


Figure 51: Special upright for switching part of track

The upright shown in Figure 51 provides additional support for a Y-junction piece to mount to, but yet it still provides enough space for a bogie to pass through the middle of the upright. Next, the analysis for this special upright will be discussed.

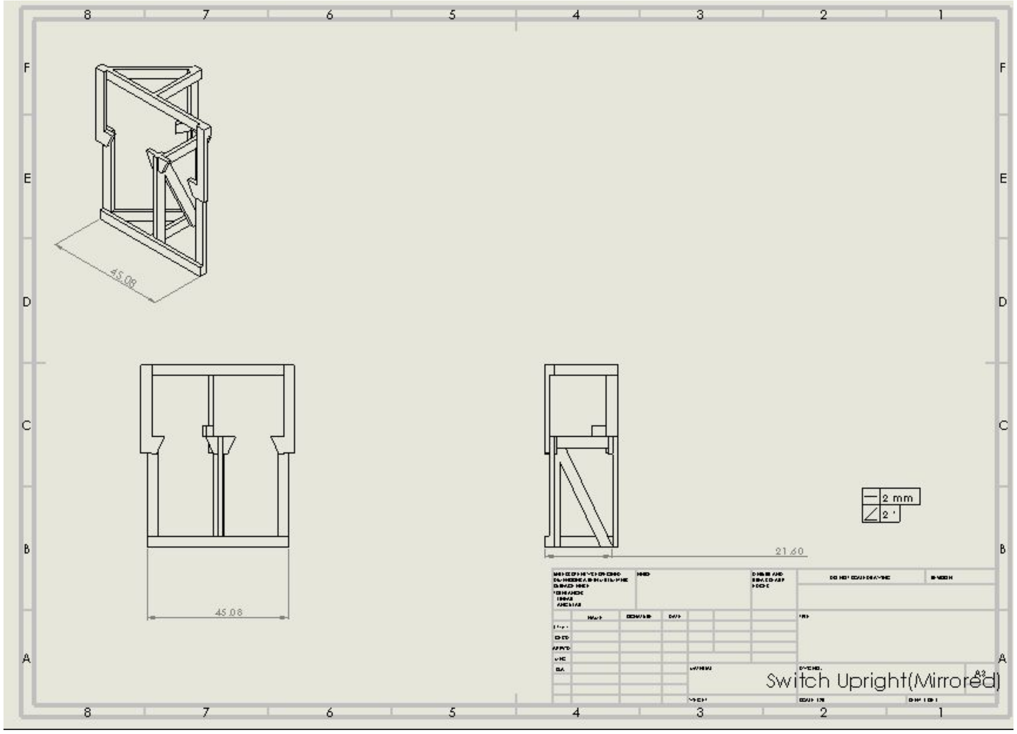


Figure 52: 2D part drawing for special upright

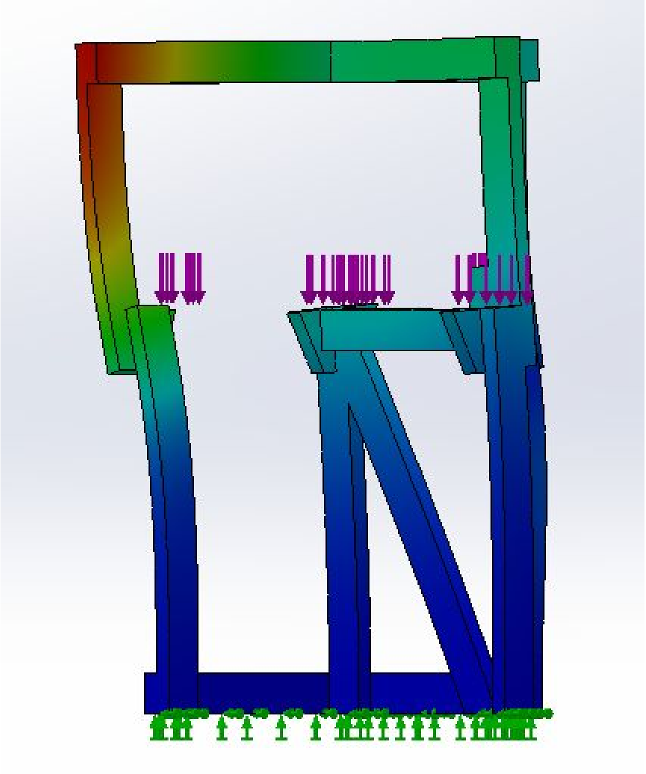


Figure 53: FEA in normal direction of special upright

The FEA analysis assumed a bogie speed of 6.7 m/s and the displacement was 0.6 mm, which is more than the standard upright, but it is practically negligible. The forces throughout all the FEA's seem really low, but when it is compared with the real life test the team did, it makes sense, more on this in the conclusion. Seen in Figure 54 is the FEA for the centripetal direction.

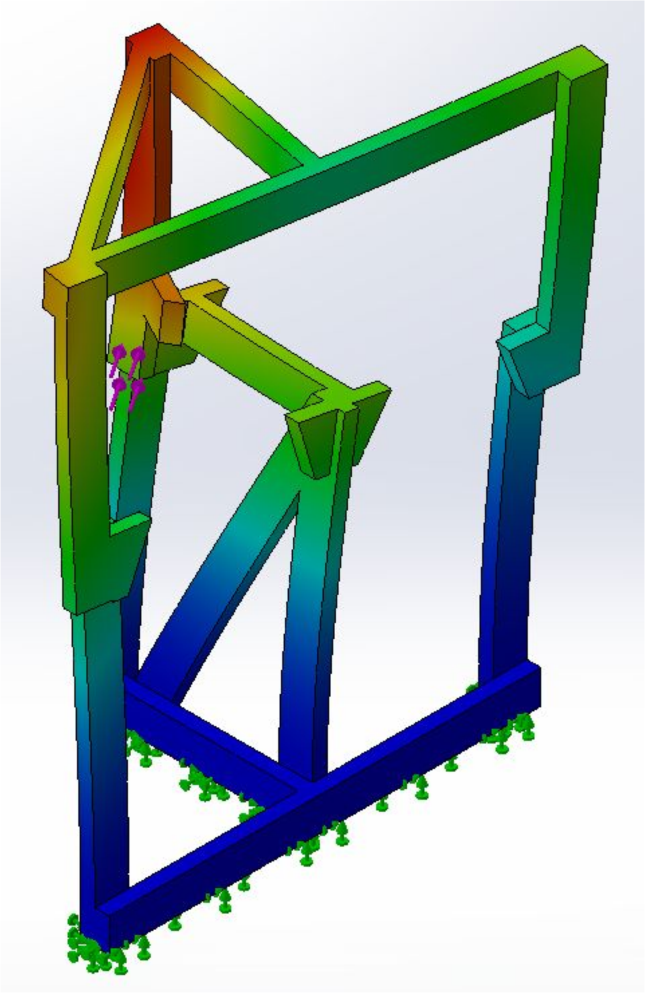


Figure 54: FEA in centripetal direction for special upright

Given the max centripetal force of 570N this upright for the transition deflects 8.5 mm. This 8.5 mm deflection is still much less than the 25 mm design specification, so the transition upright will be able to handle the forces involved with the bogie.

The manufacturing process for the uprights is rather simple as it is made of 2x4's. The plunge saw was used to cut all the uprights. In Figure 55 the completed uprights can be seen in all their glory. Please note, the lateral supports shown in the picture are temporary, and they will not be on the finished model of the track, they are simply there to aid in fabrication.

Figure 55: Actual uprights assembled with temporary lateral supports

Overall, the new uprights came out great, and they exceeded the expectations the team had. By expectations, the team means the design specifications. The overall upright cost about $14 USD to fabricate, so they were a tad more expensive than the previous design ($12 USD), but the improvements far outweigh the increased financial cost. The new uprights far exceed the design specifications, and there is no doubt in the team's mind that these uprights will serve their purpose for years to come.

VII. Conclusions and Next Steps

All in all, the goal of this project is to supply a platform of testing for other sub teams such as Power Module and Wayside. Future teams for Spartan Superway will be able to take data using the 11 meter track and further their own designs. Variables of data will be noted as velocity, acceleration, position, and displacement of the bogie, in addition to noise levels and vibration of the track itself by sensors equipped on the track. All of these platforms can help future teams understand the project on a greater level. The Full Scale team has set the ground for future teams to come in and really progress this project. Work will continue into the summer (considering the Pandemic lets up), and the next team will have a track to build a bogie for, and test other bogies on.

The Full Scale team has done extensive FEA work, and every single FEA model proved to be more than safe. As a team, small tests were done to confirm these results. For example, the team had a member physically walk on the track, so when the team observed the member walking the track and uprights were seen moving ever so slightly. The track will never see a load near a person's weight, so the design and FEA results gives the Full Scale team the utmost confidence that this will be a platform for many generations of Spartan Superway members to utilize. The world is a constantly evolving place, and Spartan Superway 2019-2020 Full Scale team has done their best to further this project, and the team is excited to see what the next batch of eager seniors brings to the table.

VIII. References

Please note, some of these sources were not used in the actual report, but they were used as a source of information and we referenced them for our own knowledge to write this report.

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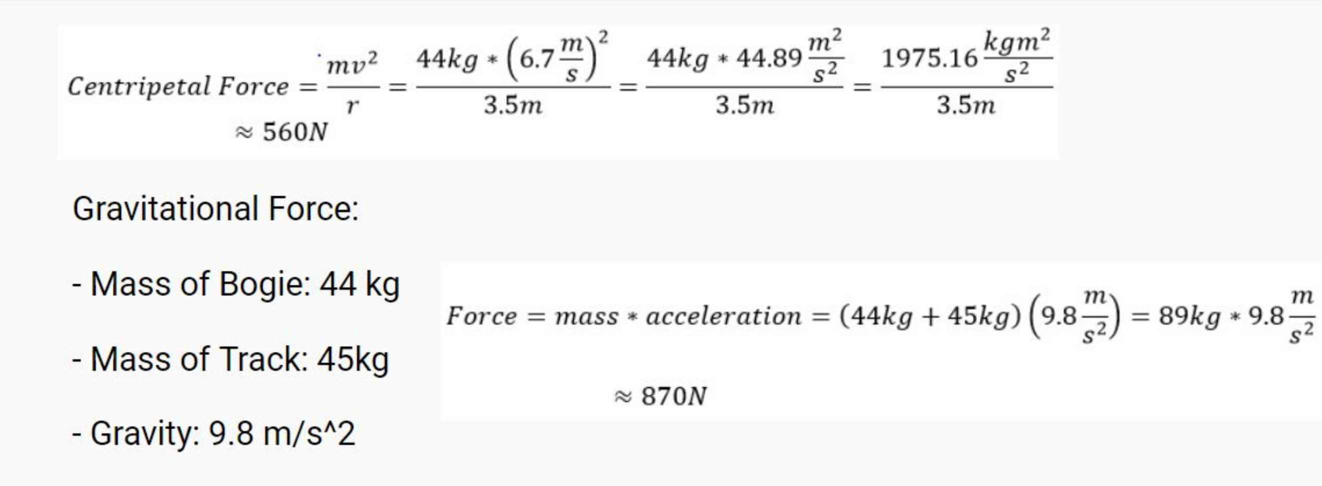
IX. Appendices

In order to complete this project, a deep analysis needed to be done, but before a deep analysis could be done, some design specifications needed to be calculated. These calculations are shown below, and to give a basic overview of what is shown, the main forces that are being dealt with in this track are the gravitational and centripetal forces, those calculations are shown below, and they are primarily for the detailed FEA.



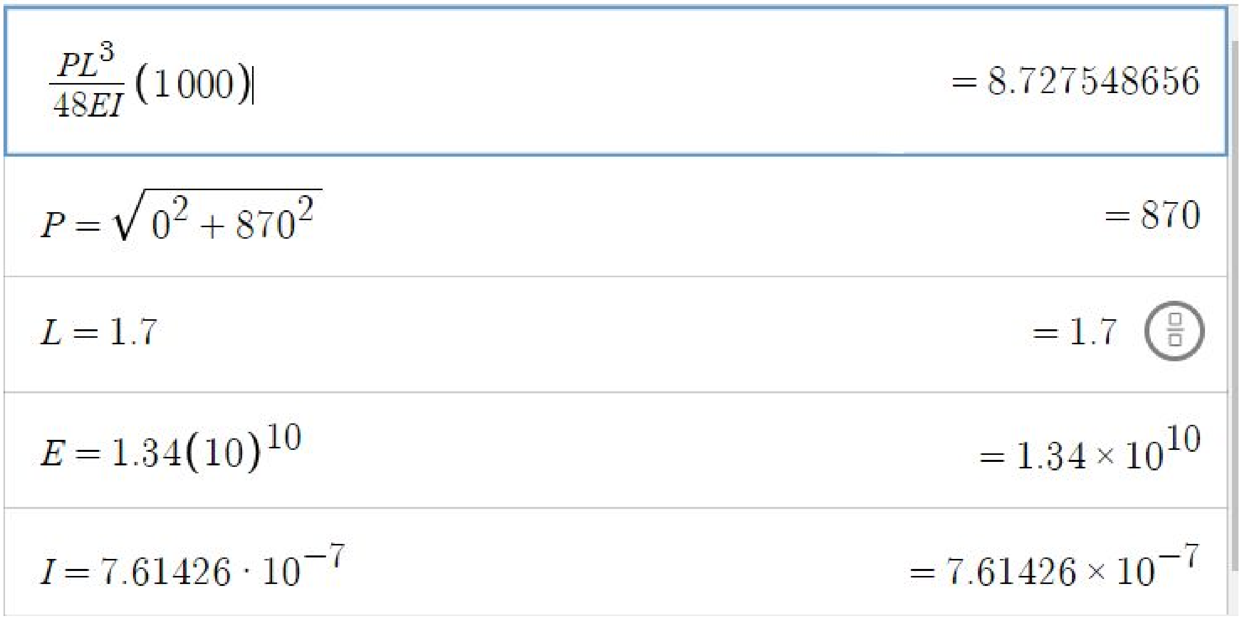
$$Centripetal\ Force = \frac{mv^2}{r} = \frac{44kg * \left(6.7\frac{m}{s}\right)^2}{3.5m} = \frac{44kg * 44.89\frac{m^2}{s^2}}{3.5m} = \frac{1975.16\frac{kgm^2}{s^2}}{3.5m} \approx 560N$$

Gravitational Force:

- Mass of Bogie: 44 kg
- Mass of Track: 45kg
- Gravity: 9.8 m/s^2

$$Force = mass * acceleration = (44kg + 45kg)\left(9.8\frac{m}{s^2}\right) = 89kg * 9.8\frac{m}{s^2} \approx 870N$$

Figure 56: Force Calculations



$\frac{PL^3}{48EI}(1000)$ $= 8.727548656$

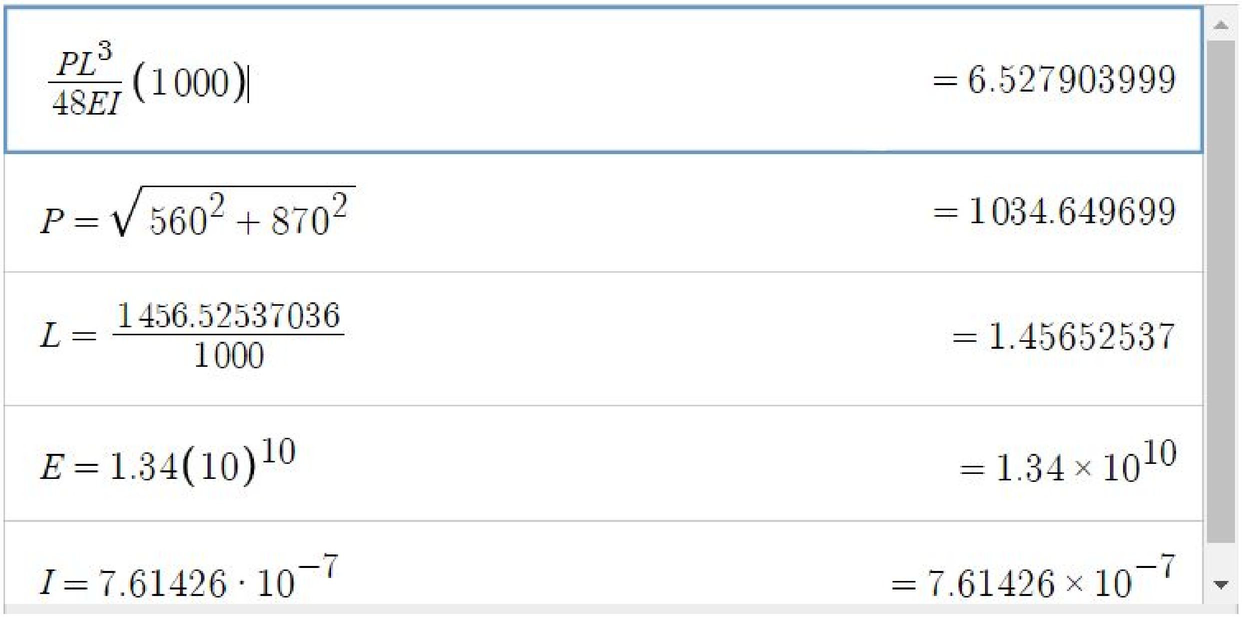
$P = \sqrt{0^2 + 870^2}$ $= 870$

$L = 1.7$ $= 1.7$

$E = 1.34(10)^{10}$ $= 1.34 \times 10^{10}$

$I = 7.61426 \cdot 10^{-7}$ $= 7.61426 \times 10^{-7}$

Figure 56a: Deflection Calculation for Straight FEA (Units are in N and m)



$\frac{PL^3}{48EI}(1000)$ $= 6.527903999$

$P = \sqrt{560^2 + 870^2}$ $= 1034.649699$

$L = \frac{1456.52537036}{1000}$ $= 1.45652537$

$E = 1.34(10)^{10}$ $= 1.34 \times 10^{10}$

$I = 7.61426 \cdot 10^{-7}$ $= 7.61426 \times 10^{-7}$

Figure 56b: Deflection Calculation for Curved FEA (Units are in N and m)

Name	Quantity	Cost per Unit	Total Cost (w/o tax)
2 x 4 Douglas Fir Wood	40	$24	$960
Gorilla Glue - 62000	5	$5	$25

2.5 x ½” Wood Screws	100	$10	$50
Waterjet Abrasive Bags	5	$50	$250
			$1285

Figure 57: Bill of Materials

Common Name(s):	Douglas-Fir
Scientific Name:	Pseudotsuga menziesii
Distribution:	Western North America
Tree Size:	200-250 ft (60-75 m) tall, 5-6 ft (1.5-2 m) trunk diameter
Average Dried Weight:	32 lbs/ft^3 (510 kg/m^3)
Specific Gravity (Basic, 12% MC):	.45, .51
Janka Hardness:	620 lb_f (2,760 N)
Modulus of Rupture:	12,500 lb_f/in^2 (86.2 MPa)
Elastic Modulus:	1,765,000 lb_f/in^2 (12.17 GPa)
Crushing Strength:	6,950 lb_f/in^2 (47.9 MPa)
Shrinkage:	Radial: 4.5%, Tangential: 7.3%, Volumetric: 11.6%, T/R Ratio: 1

Figure 58: Datasheet of Plywood