ASME Shell Eco-Marathon

Final Report

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DISCLAIMER

ABSTRACT

Team 007 collaborated with the American Society of Mechanical Engineers (ASME) club at OSU to produce an improvement to their Shell Eco-Marathon (SEM) prototype vehicle. The vehicle competes in a global competition where teams aim for the most energy-efficient vehicle possible. The goal of this project was to improve the vehicle in a quantifiable way using Hewlett Packard's (HP) 3D printing sponsorship. The capstone team's area of focus was the front axle system, comprising three main components: the tire shields, the shield mounts, and the axle mount.

For the tire shields, the final design consisted of 3D-printed curved edges attached to a flat polycarbonate sheet with carbon fiber rods fanning out from the edges. The design resulted in an improvement of visual appearance, rigidity, and ergonomics. For the shield mount, the final design utilized HP's sponsorship due to the complex geometry and was attached to the axle mount instead of the steering brackets. The attachment location of the shield mounts changed from a mobile point to a fixed point which vastly increased the stability and legroom for the driver. For the axle mount, the final design is a theoretical option for the ASME club to implement in the future. The design uses the same manufacturing process as the current mount but is slimmed down to reduce bulk and increase legroom. The sleek design reduces the weight of the front axle system which is a quantifiable improvement. After multiple iterations, the team settled on a final design that meets all of the customer and engineering requirements.

ACKNOWLEDGEMENTS

The capstone would like to acknowledge our project advisor, Dr. Chris Hoyle, and our faculty mentors, Chris Holm and Mark McGuire, for guiding us through our project. The team would also like to acknowledge our sponsor, HP, for providing the 3D printing service and the ASME club president, Andrew Goff, for collaborating with the team.

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1 BACKGROUND

1.1 Introduction

The SEM is a global energy efficiency competition in which OSU's ASME participates. It is one of the world's leading student engineering competitions and was first launched in 1985. More than 100,000 students spread across hundreds of universities in over 60 countries have participated in the marathon. Students design, build, and operate energy-efficient vehicles and compete for the best energy efficiency result in their vehicle class and energy category [1].

The two-vehicle categories to compete in are the prototype class and the urban concept class. The prototype class's focus is on record-breaking energy efficiency. The teams aim to build the most aerodynamic cars possible within the competition guidelines. On the other hand, the urban concept class takes into account city driving and is focused on making normal passenger cars as efficient as possible. The energy categories available are internal combustion engines, battery electric, and hydrogen fuel cell [1]. Currently, the ASME club builds the club's vehicle under the prototype class using battery electric.

The purpose of this project is to identify where the vehicle can be improved upon and design a solution for it. The current vehicle has been worked on in previous capstone projects, resulting in updates to various components. The team has consistently come in second place for the past few years and has enlisted the help of capstone student projects to improve their chances of success in competition. The client's biggest area of concern is the front tire axle assembly (*see Figure 1*). The tire shields were constructed rudimentarily to fulfill the competition requirement c of Article 41: "Wheels located inside the vehicle body must be isolated from the Driver by a bulkhead and must not touch the chassis or body" [2]. Their last-minute construction leaves much room for improvement. In addition, the front axle itself is bulky and could be an area for weight reduction. Overall, the design challenge is to improve the front tire axle system with a quantifiable reduction in the number of parts and/or weight, with part of the system machined using 3D printing.

Figure 1. Original front axle assembly in OSU's Eco-Marathon vehicle.

Upon completion, this project will have addressed the client's concerns regarding the front axle system and improve the vehicle in a quantifiable way. In addition, this project will highlight the capabilities of HP's nylon 3D printing and how it can be implemented in the future. As a whole, this project will satisfy the client's needs while providing insight into the 3D printing process for both the client and sponsor.

1.2 Project Scope

The stakeholders for this project consist of the project team: Abby Chunestudy, Trent Kinion, and Kate Potter; the course instructors: Chris Holm and Mark McGuire; the technical advisor: Dr. Chris Hoyle; and the project sponsors: the ASME club and HP. This project is held within the budget of the ASME club, as they will be the ones supplying the funds. Their allotted budget is $500 and does not include HP's 3D printing or any machined parts. This means the money will go towards any connection points and materials for the shields.

The main risk of this project involves scope creep, as there are multiple areas of concern in the front axle. The team will propose a design solution for the axle mount but will not produce a physical product. This is because the ASME club might change components in the future that affect the mount, leaving the new design useless. By proposing a design solution to implement in the future, the capstone team and the ASME club reduce time wasted. This means the team will base the tire shield mounting on the current axle mount. Overall, a physical design solution to the tire shields and their mounting point will be produced as well as a proposed solution to the axle mount that can be implemented in the future.

2 DESIGN PROCESS

2.1 Customer Requirements

The first step in the design process was to meet with the clients and understand their expectations for the outcome of this project. The team first met with Dr. Hoyle to establish the customer requirements (CR's). The primary requirement for this project was that there must be some measurable improvement made to the front axle assembly of the vehicle. Additionally, the ASME club wanted an improved physical appearance inside the vehicle and to simplify assemblies where possible. These general guiding requirements were broken down into simpler categories and put in the House of Quality (*see Table 1*). There were also a few Shell Eco-Marathon regulations that needed to be considered for the new design, so these regulations were also added as CR's [2].

From the customer requirements, engineering specifications (ES's) were generated. Engineering specifications were used to set quantifiable limits and goals for this project. At the completion of this project, the engineering specifications were assessed to determine the success of the final design. All CR's and ES's can be seen below in *Table 1*.

Table 1. House of Quality detailing customer requirements and their associated engineering specifications, along with their tolerances and weights.

Customer Requirements (CRs)					
CR#	**CR description using complete sentences**	**Weight (250 total)**	**Matching Engineering Specification**	**Targets with Tolerances**	**Test Procedure Number**
1	All materials and hardware purchased must be within the budget provided by OSU's ASME	50	Manufacturing cost ($)	< $500	1
2	Reduce the weight of the vehicle	25	Weight of car (lb)	< 11.5 lb	2
3	Simplify the design of the front axle assembly	25	Number of parts in assembly (#)	< 15	3
4	Meet the competition exit time requirements	50	Time to exit the vehicle (s)	< 10s	4
5	Meet the competition design and driver safety requirements	50	Wheels do not have contact with the bulkhead separating the driver	Yes/No	5
6	Improve the stability of the tire shields	15	Shields do not heavily rattle while driving car	Yes/No	6
7	Must have at least one 3D printed part	25	Number of 3D printed parts (#)	> 0	7
8	Improve the visual appearance of the vehicle	10	Better fit and finish - aligns with club standards	Yes/No	8
	Sum (should be 250)	250			

2.2 Concept Generation

Guided by the customer requirements and engineering specifications, the team began generating design concepts. Rather than try to create design concepts for the system as a whole, design concepts were broken down into three components: wheel shields, shield mounts, and axle mounts. Designs for all components had to meet customer requirements, but each component had its own focus. Because of their flimsy and poorly executed design, the main focus of the wheel shields and mounts was to improve stability and physical appearance. The axle mount is very stable, but it is over-designed, uses too much material, and has too many assembly components. Therefore, the focus for the axle mount was to decrease the weight of the assembly by removing material as well as simplify the design to minimize the number of parts in the assembly.

With these guidelines, each team member generated two to three concepts for each component. Design concepts that were too similar to each other were combined into a single concept. Design concepts for each component are detailed below.

Shield Concepts:

- Thermoform plastic
- Tubing reinforcement
- Fiberglass mold with wire supports
- Roll-up wheel shields
- 3D printed curved edges with carbon fiber sheets

Shield Mount Concepts:

- Secure to axle mount
- Secure to chassis
- 3D printed mount adapter
- 3D printed mount attached to axle

Axle Mount Concepts:

- Fusion 360 generative design
- Two separate mounting brackets
- Simplify mounting brackets
- Water jetted aluminum with FEA
- Cast titanium

2.3 Concept Selection

After generating design concepts for each component, the team began a down selection process to reach a final design. The team decided to create a Pugh Matrix for each component for down selection. *Table 2* shows the Pugh Matrix used for the shield mount. In the Pugh Matrix, design concepts were evaluated against a baseline (the original design). The team decided what criteria were most valuable for the success of a design. Each concept was evaluated by comparing its performance in a certain criteria to the baseline. For each criterion, the concept was rated as either worse, better, or the same as the baseline. Ratings were added up for each concept, and then concepts were ranked against each other. Before committing to the highest-ranked design concept, the team conducted a secondary subjective evaluation of each concept. This was because the Pugh Matrix criteria are not weighted based on their importance, so the team wanted to ensure that the highest-rated concept was in fact the best option. After these evaluations, the final design concepts for this project were selected.

Table 2. Pugh matrix for the shield mount.

Pugh Matrix - A Decision Matrix

Problem/Situation: Original Tire Shields Mounting

	Criteria	Baseline Current Design	Alternatives 1: Secure to axle mount	Alternatives 2: Secure to chassis	Alternatives 4: 3D printed mount adapter	3D printed mount attached to axle	Totals	Rank
1	Price	0	0	–	–	–	-3	6
2	Durability	0	+	+	0	+	3	1
3	Low Weight	0	0	–	+	0	0	3
4	Driver clearance	0	+	–	0	+	1	2
5	Feasibility	0	0	–	0	–	-2	5
6	Rigidity	0	+	+	0	+	3	1
7	Ease of installation	0	–	–	0	+	-1	4
8	Novelty	0	0	+	+	+	3	1
	Low number of parts	0	0	–	0	–	-2	5
9	Safety	0	0	+	0	0	1	2
		Totals	2	-2	1	2		
		Rank	1	3	2	1		

For the tire shields, it was decided the best concept alternative was 3D-printed curved edges with carbon fiber sheets. This solution will provide a smoother transition between the curved and flat section and the carbon fiber supports will extend from the center to provide additional rigidity.

The best concept alternative for the tire shield mounting was a 3D-printed mount attached to the axle. It was decided the shield mount is best manufactured through 3D printing, as it can produce complex geometries. Specifically, the PA-12 nylon material used for the printing is capable of high-density, strong parts with balanced property profiles [3]. Additionally, attaching the mounting to a fixed point will prevent the shields from interacting with the chassis or driver and provide additional stability.

For the axle mount itself, the best concept alternatives were simplified mounting brackets and water-jetted aluminum with FEA. The team will incorporate both, as the current design can be simplified in its mounting points as well as the overall shape. By directly attaching the axle to the chassis, it effectively removed excess parts, and water-jetted aluminum can be redesigned to fit a simpler, smaller shape.

3 DESIGN PROPOSAL – First Term

The proposed designs of the three components will be discussed in this section. The wheel shield design will be more rigid and lightweight than the original. The new shield mounts will stop interference between the shields and the driver. The axle mount will be more lightweight than the original and will require fewer parts in its assembly. The overall appearance of the front axle assembly will be much improved.

3.1 Wheel Shields

3.1.1 Original Design

The original wheel shields were constructed using clear plastic and metal strips to attach a curved edge to the flat section. The right-hand side of the vehicle contains the steering arm so a cut was made through the right shield to accommodate the steering arm. The cut creates an unsightly appearance and affects the rigidity of the shield (*see Figure 2*).

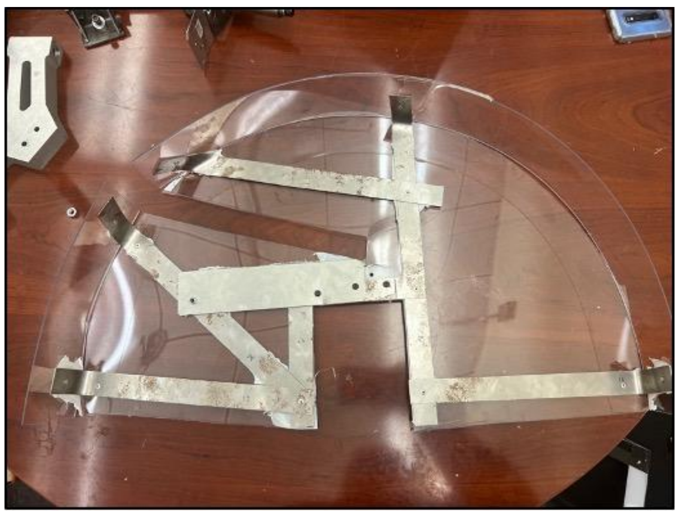

Figure 2. The original right tire shield, displaying the cut-out portion for the steering arm.

3.1.2 First Design Iteration

The design concept chosen from the down-selection process consisted of a flat front plate, carbon fiber reinforcement rods, and 3D-printed curved edges. The carbon fiber rods would epoxy to the front plate to increase rigidity. The curved edges are attached to the front plate with thin slots that the plate can slide into. Due to the size limitations of the 3D printer, the curved edges were split into four pieces that were designed to clip together (*see Figure 3*). The geometry of the steering arm would force the right shield to have a large cutout through the middle just like in the original model. To prevent this, the team proposed new steering arm geometry that would require a much smaller cut through the wheel shield. A prototype of the first design iteration can be seen in *Figure 4*.

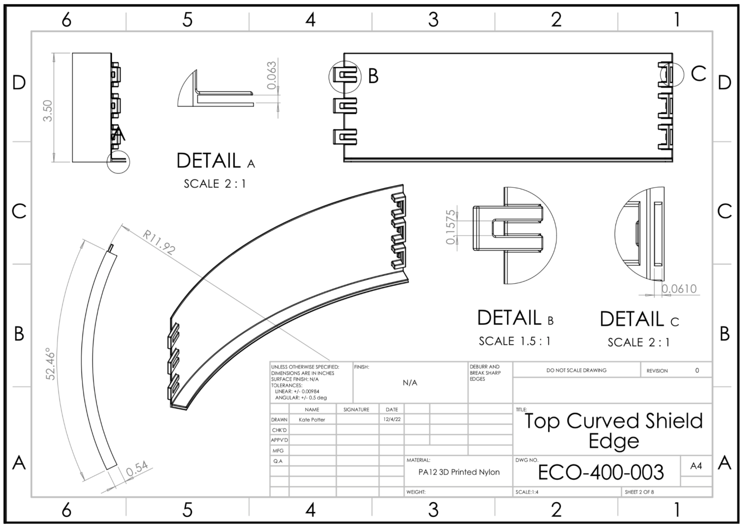

Figure 3. Original design of curved shield edges.

Figure 4. The proposed design solution for the tire shields, including the redesigned steering arm.

3.1.3 Final Design Iteration

After a prototype of the curved edges was printed, the team saw that the clips were not designed with enough clearance, so the clips could not connect. Rather than fixing the clips, the team realized that the clips were not actually needed. The intention of the clips was to hold the curved edge pieces together, but the curved edges were already going to be held in-place where they were attached to the front piece of the shield, rendering the clips useless. The clips were removed from the curved edges and flat mating faces were put on the edges instead.

The flat ABS sheet used for the face of the shield was more flexible than expected so an additional carbon fiber rod was added to each front surface and the rods were arranged in a new fanned-out pattern in order to increase rigidity (*see Figure 5*). Additionally, slots for the carbon fiber rods to slip into were added to the sides of each curved edge piece. This addition made the rods more secure.

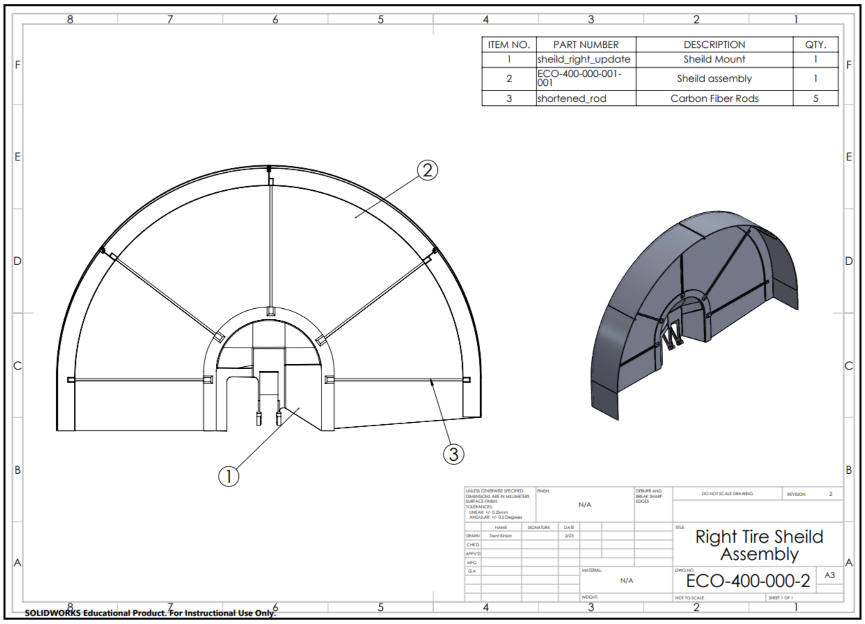

Figure 5. Update full shield assembly showing fanned carbon fiber rods

After more prototyping, it was determined that the thickness of the flanges needed to be increased so that the curved edges would better stabilize the front sheet. This last design change is the final iteration of the wheel shields. The final design of the curved edges can be seen in *Figure 6*.

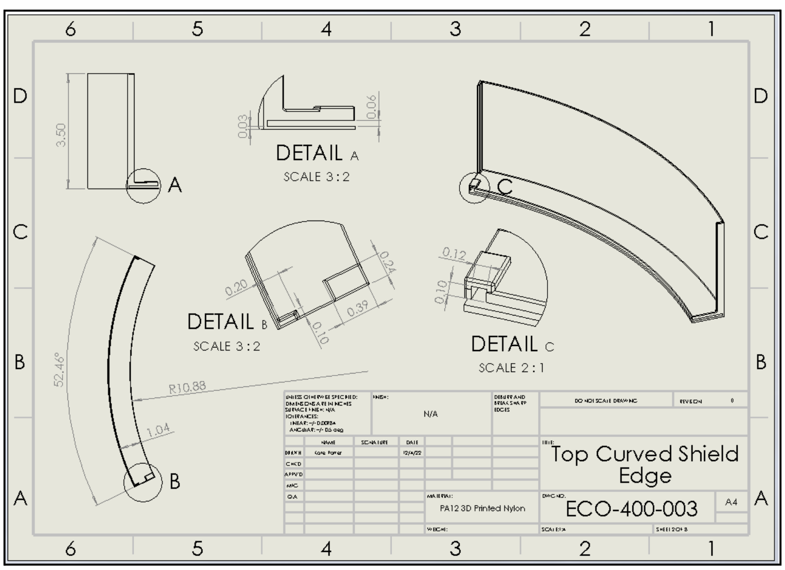

Figure 6. Updated, final design of curved shield edges.

The ASME club has already decided they will be redesigning the steering later on, so the team decided to remove the steering arm from the front assembly so that a cut would not have to be made through the right shield. This way, the ASME club can adjust the design of the shields however they want after the new steering system is designed.

3.2 Shield Mounts

3.2.1 Original Design

The previous mounting design was a simple steel L-bracket as seen in *Figure 7*. The pitfalls of this design were that the corners of the bracket dug into the legs of the driver and, since it was attached to the kingpin directly, it would move with the steering. This created a lot of rattle and got in the way of the driver while taking corners. While analyzing where improvements could be made with HP 3D printing, the bracelets were one of the best candidates.

In the new design, the team tested out a new mounting structure with a single screw that clamped the part to the axle mount. The flange was a simple flat section that would be used to glue the shield to it. One of these was printed for prototyping purposes, as seen in *Figure 8*.

Figure 7. Original Shield Mount

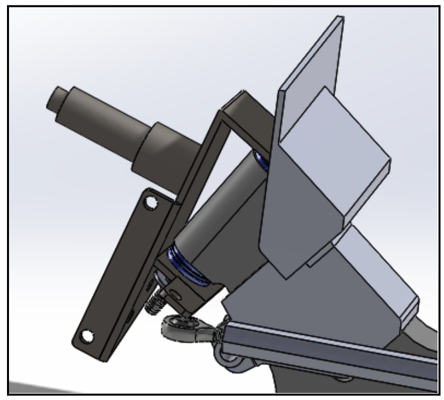

Figure 8. CAD model of the new shield mount.

3.2.2 First Design Iteration (Delivered Product)

The team saw several improvements that could be made from the first prototype. Firstly, the team decided to make the clamp two screws, because the mount kept swiveling while being clamped. The new design interaction takes advantage of the limitless geometry a 3D-printed part can have and used lofting to connect a rounded shield flange to a rectangular mount. The new flange slides into the shields and has slots for carbon fiber rods. The new flange is the same weight as the prototype, is stiffer, and provides more protection for the driver compared to the original design and the first prototype. *See Figure 9* for the new design

The team has two of these printed and was pleased with the final products. These were glued to the final assembly and met all of the specifications set by the team.

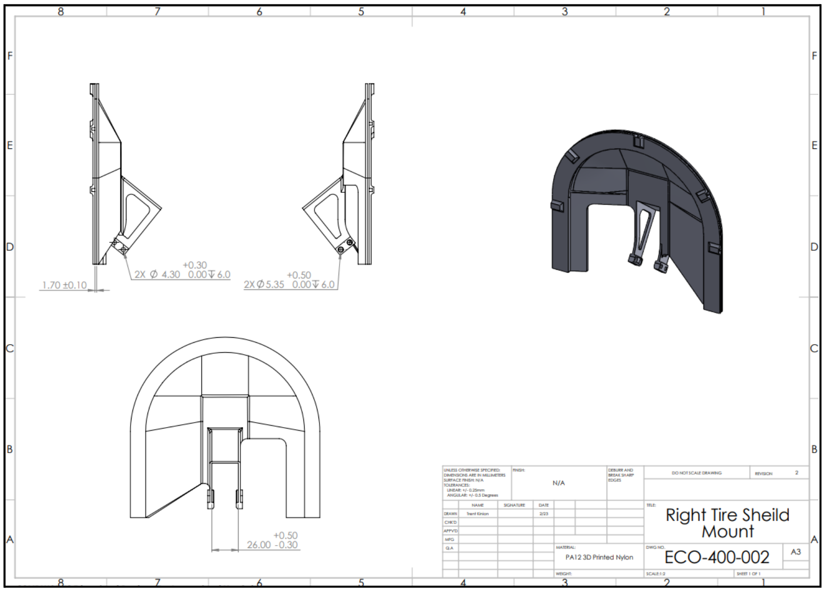

Figure 9. Delivered Shield Mount

3.2.3 Final Design Iteration

While testing the mounts the team noticed that once the ASME club fixes the steering limitations of the car the tires could contact the new tire shields. To fix this problem a new mount was made that brought back the shield mounting location without adjusting anything else. This design could be ordered from HP at any time and be implemented when needed. See *Figure 10* for the new design that was not printed.

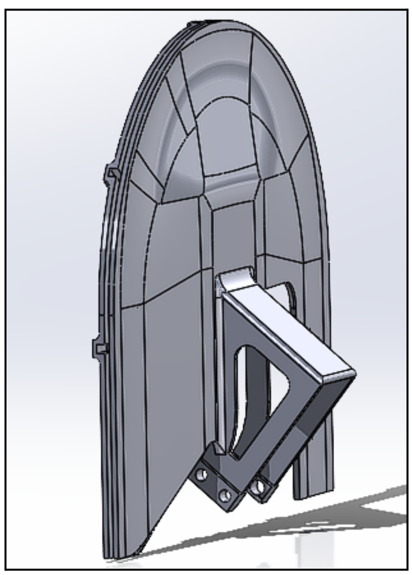

Figure 10. Updated shield mount design

3.3 Axle Mount

3.3.1 Original Design

The original axle mount design was made up of a water-jetted aluminum frame, four mounting brackets, four screws for securing the brackets to the frame, and four more screws to secure the brackets to the chassis, totaling thirteen components in the assembly (*see Figure 11*). The number of components in this assembly made installation very time-consuming. The team saw an opportunity to remove excess material from the frame and simplify the design.

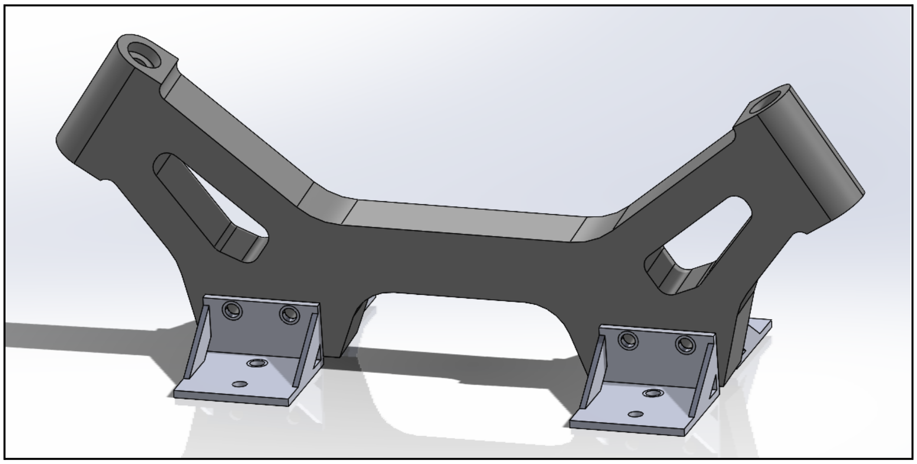

Figure 11. Original axle mount CAD assembly

3.3.2 First Design Iteration

The axle mount design proposed in the first term of this project had fewer assembly pieces and was more lightweight. This design replaced the mounting brackets with a single mounting plate welded to the bottom of the axle mount frame (*see Figure 12*). The mounting plate would attach to the same bolting locations already on the vehicle chassis. This design change reduced the number of assembly components from thirteen down to just five (combined axle mount frame and mounting plate and four bolts). Eliminating the mounting brackets helped to reduce the weight of the axle mount assembly. To reduce the weight even further, the arms of the axle mount frame were thinned out and the center of this component was moved down to the base plate. This design change also offered more room to the driver. The 2021-2022 capstone team ran a finite element analysis (FEA) on the original axle mount frame to ensure this part would not deform or fail underestimated loads. The same FEA was simulated for the new design to ensure the same requirements. The FEA concluded that the new design would not fail or deform under load. The original axle mount frame had a factor of safety of 3.8, and the first iteration design had a factor of safety of 2.

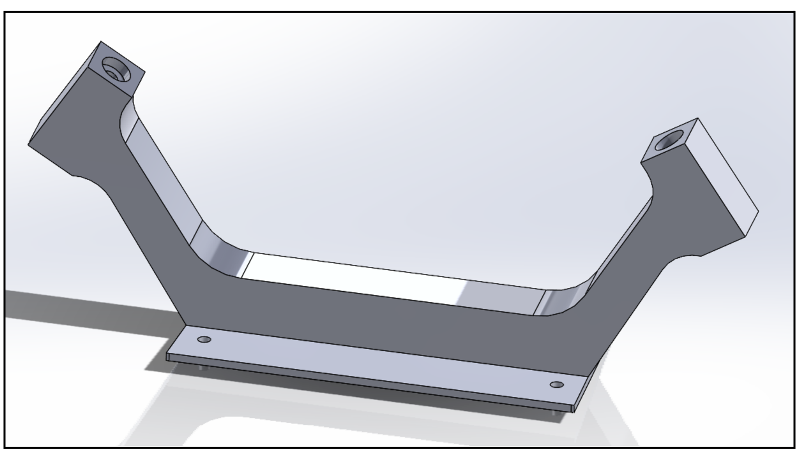

Figure 12. CAD model of the first proposed axle mount design

3.3.3 Final Design Iteration

The first axle mount design met all the requirements the team had set. However, the results of the FEA showed there was still room for improvement. The base of the frame was experiencing very low levels of stress and there were large stress concentrations at the bend of the arms (*see Figure 13*). The final design decreased the thickness of the base and widened the bends of the arms. Pockets were put in the arms to remove additional material (*see Figure 14*). The magnitude of stress concentrations on the final design is much less than those from the first iteration (*see Figure 15*). The final design resulted in more weight reduction and a higher factor of safety than the first iteration.

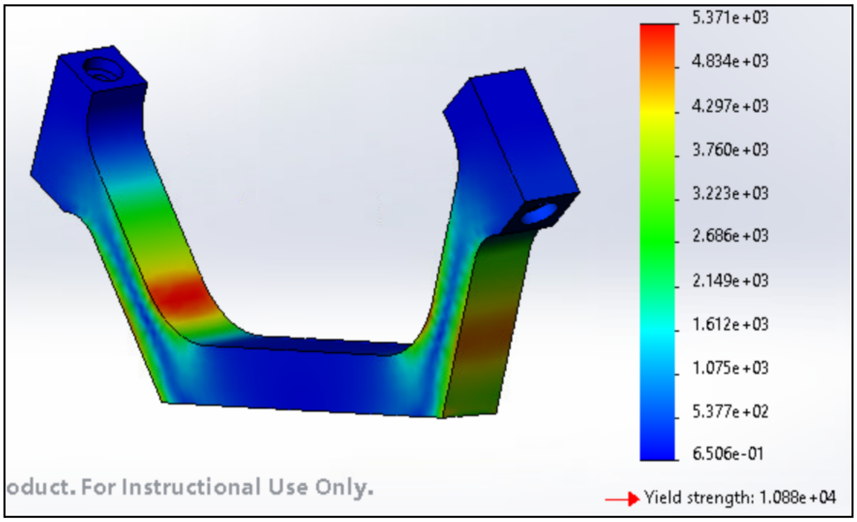

Figure 13. FEA stress map results from the first proposed axle mount frame design (scale is in psi)

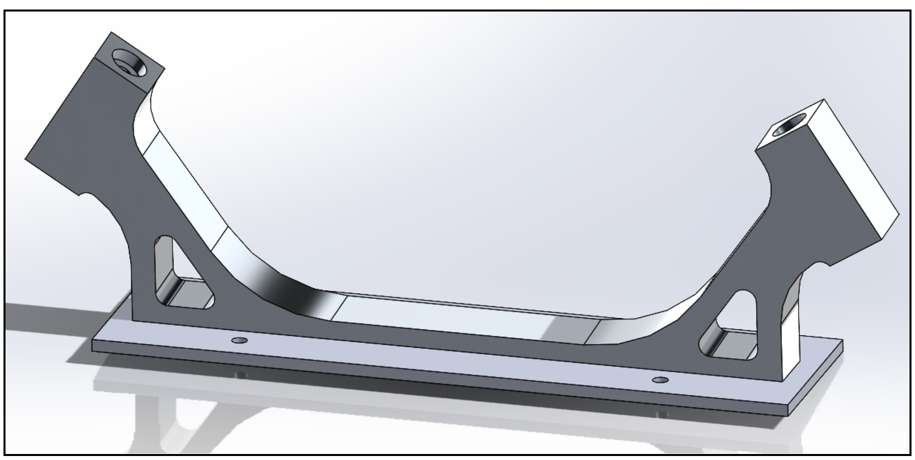

Figure 14. Axle mount final design

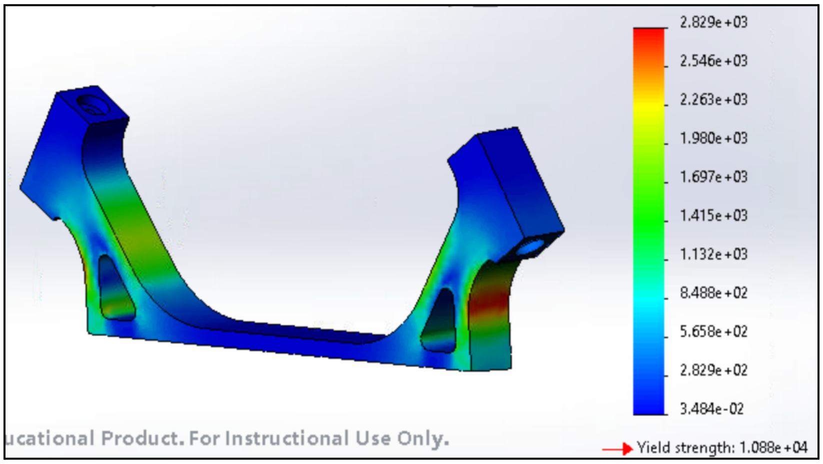

Figure 15. FEA stress map results from the final axle mount frame design (scale is in psi)

Later on in this project, the team discovered some errors in the FEA simulation and had to correct them and re-run all simulations. The setup of the original FEA placed 60 lb-f on the inner bore of the wheel mount location and 100 lb-f on the top surface of the wheel mount location (*see Figure 16*). After some discussion, the team realized that the 100 lb-f should be acting on the bottom surface of the wheel mount location because the force from the weight of the car and driver pushes up on the axle mount frame, not down (*see Figure 17*). When discussing this change with the client, the client added that 100 lb-f each for the flat surfaces was too conservative, so this force was increased to 200 lb-f each in the FEA simulation. This change was applied to both the final design as well as the original model to ensure results were being compared to the correct baseline. Only some minor changes were made to the final design after running the updated FEA, *Figure 18*.

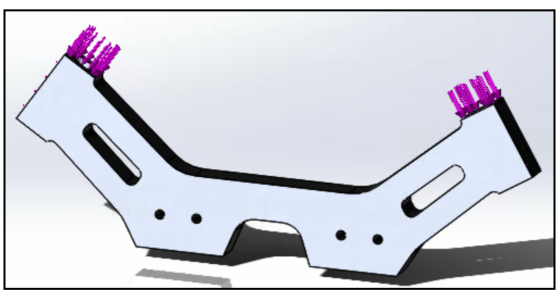

Figure 16. Original FEA simulation (original mount)

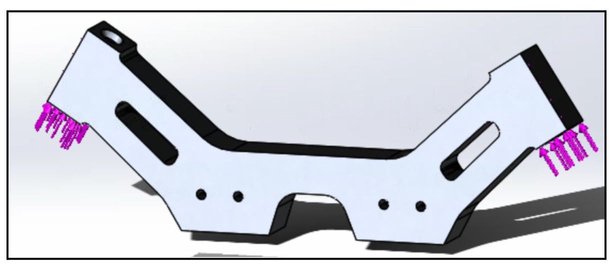

Figure 17. Updated FEA simulation (original mount)

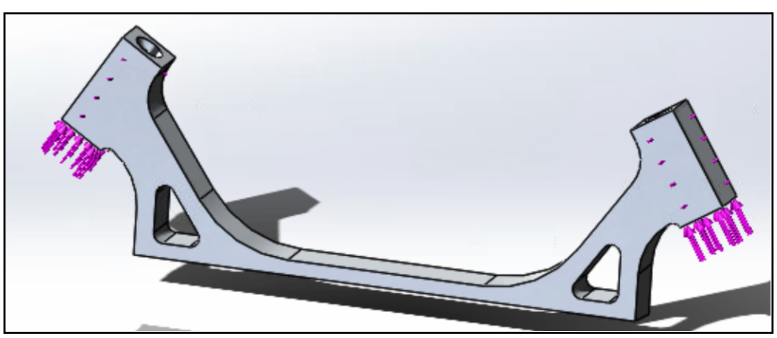

Figure 18. Updated FEA simulation (final design)

4 Design Solution

In this section, the final design solution will be displayed along with the associated proof of satisfaction. Thorough testing was conducted to ensure all ES's were met which signifies the completion of this project.

4.1 Description of Solution

The final design of this project encompasses a physical product for the wheel shields and a proposed theoretical design for the axle mount.

For the wheel shields, the curved 3D printed edges and 3D printed mount is attached to the ABS sheet via carbon fiber rods and epoxy (*see Figure 19)*. The mounts attach to the axle arms and are secured via bolts and heat set inserts which makes the shields removable. The epoxy and carbon fiber rods produce an extremely rigid result, while the mount produces a stable result with increased legroom.

Figure 19. Final wheel shields in the vehicle.

For the axle mount, the final design is a simplified aluminum water-jetted piece welded to a sheet metal aluminum base plate. The base plate has four mounting holes where it will screw into the body of the chassis. This design makes installation much simpler. The geometry of the water-jetted frame was simplified and slimmed down to reduce weight. The final design is much simpler and lighter than the original design while still maintaining the same factor of safety.

4.2 Project Results

To prove that all engineering specifications from the House of Quality had been met, this team had to have some kind of assessment to verify each ES. Some assessments were as simple as a "yes or no" to if the project met that ES, whereas other assessments required testing to prove the ES had been satisfied. All ES's have been satisfied with this project and the ES testing procedures and results can be found in Appendix A.

Overall, the newly assembled shields are more robust, better looking, and of a higher quality than the original shields. The team used lighter materials and created a more symmetrical design to help complete all ES's. Compared to the original shields, the final design is 10% lighter, 57% quieter, and has a 100% approval rate from the ASME club. The carbon fiber rods and epoxy severely increase the rigidity of the shields which contributes to noise reduction. Additionally, the mounts provide increased comfort for the driver, as the design has curved, smooth edges that don't cut into the driver's legs.

The theoretical axle mount design is lighter, simpler, and just as strong as the original design. Determined from the FEA results, the final axle mount design has a factor of safety of 3.8 which is the same as the original design. The new design is 1.2 lbs lighter than the original which is equivalent to a 47% reduction in weight. The base plate installation is much simpler and faster because only four bolts are required.

5 LOOKING FORWARD

After completing this project Team 007 has a few suggestions and notes regarding the future of the front axle assembly and steering system.

There are a few issues with the vehicle that were noticed but not addressed in this project because it was outside of the project scope. The first of these issues is that the wheels make contact with the chassis when the vehicle is turning which interferes with the turning radius. This is an issue because SEM guidelines state that the vehicle must have a turning radius of 8 m or less. The vehicle currently has a turning radius of approximately 10 m. Because there is so little room inside the body of the vehicle the best course of action may be to move the front tires to the outside of the vehicle. While working on prototypes, it was noticed that the chassis is asymmetrical. Additionally, CAD assemblies provided by the previous capstone team are not accurately dimensioned. Luckily, the asymmetry of the chassis did not greatly impact the final design, but the inaccurate CAD models did. The axle mount and shields were designed to fit with the CAD assembly, so the first prototypes did not fit in the vehicle as intended. The axle mount frame CAD model of the original design was not the same as the part actually being used in the vehicle. A new CAD model of the original axle mount frame was made by carefully measuring the actual component. For all future projects on the vehicle, it is recommended to verify all measurements and CAD models before proceeding with any new designs.

If the ASME club uses the same or a similar axle mount system in the future, the team recommends replacing the original axle mount assembly with the theoretical model described in this paper. The new model is lighter, simpler to assemble, and looks much cleaner. CAD files of this part will be left for future club use should they decide to use or alter the theoretical model.

The major takeaway from this project is that the ASME team now has a connection and experience working with HP making Nylon based 3D printed parts. The ASME team has a lot of updates to make to the car to be able to compete next year and being able to utilize rapid prototyping and manufacturing will be helpful in completing everything. The capstone team demonstrated the capability of the material that HP prints with and the complex geometry that 3D printing can achieve. The current vehicle has many small pieces made out of scrap pieces of wood and plastic that would be perfect candidates for 3D printing and the team advises the club or future capstone teams to explore replacing these items with 3D printed parts from HP.

6 CONCLUSIONS

The goal of this project was to improve upon the ASME club's prototype vehicle in a quantifiable way. Throughout many iterations, this capstone team has successfully delivered a product that accomplishes what was agreed upon from the start. Using HP's sponsorship, the team transformed flimsy and heavy tire shields into a rigid and stable outcome that is not only lighter but more visually appealing. Additionally, the ASME club now has an improved design for the axle mount which can be implemented in the future and can use the 3D printing knowledge gained on projects in the future.

Throughout the design process, safety was kept in mind, as our component is operated by humans and any failure could have a negative impact on someone's life. To prevent harm, the team designed around potential failures using a Failure Modes and Effects Analysis (FMEA) which highlighted common sources of error and their severity (see Appendix B). Through this, the team was able to keep in mind how the device would fail during use and then design around it. The shields would fail at connection points due to applied stress from the driver, meaning the epoxied areas required enough strength to withstand manual manipulation. Additionally, the axle mount would fail at welding locations which can be circumvented by placing the connection points at low-stress locations. Although none of the components will be placed under high-stress conditions, it is still necessary to apply engineering design principles to prevent future harm.

Although the team believes there are many improvements to be had it is believed that this project made strides toward creating a car that is safer and better in several measurable ways as proved by the completed engineering specifications. One of the largest takeaways that was not encompassed by the engineering specifications is that this project provided a proof of concept by using HP's 3D printed parts as a mainstay in future design tasks the club encounters. The team provided great detail and constant communication to the club on how to communicate with HP for parts and showed that the nylon-based material is applicable to most parts of the car. This project will pay dividends down the line when an increasing portion of the car is made of Nylon based 3D printed parts all because this year's capstone team took a leap into the world of 3D printing from HP Inc.

7 REFERENCES

[1] n.d., “Our Mission.” from https://www.makethefuture.shell/en-gb/about

[2] 2023, “Shell Eco-marathon 2023 Official Rules Chapter 1.” Shell, from https://www.makethefuture.shell/en-gb/shell-eco-marathon/global-rules

[3] 2018, “HP 3D Printing Materials”, HP Development Company, L.P., Palo Alto, CA.

8 APPENDICES

8.1 Appendix A: Engineering Specifications Verification Table

ES #	Requirement	Baseline	Testing Procedure	Result	Pass or Fail
1	Total costs must be within a $500 budget	N/A	N/A	Total costs were $104.12 (See Appendix C)	Pass
2	Finale steering assembly must weight less than original	11.5 lbs	Weigh baseline and final assembly	10% weight reduction	Pass
3	Final axle mount assembly must have fewer parts than the original	13 components	N/A	8 fewer parts	Pass
4	Driver must be able to exit the vehicle in less than 10 seconds	N/A	Time a team member exiting the vehicle	8.86 seconds to exit the vehicle	Pass
5	Wheels must not make contact with the wheel shields	N/A	Measure minimum distance between wheels and wheel shields when vehicle is at maximum turning angle	1.5 cm of minimum clearance	Pass
6	Shields are less noisy and do not heavily rattle while driving the vehicle	23 decibels	Using a decibel measuring app, measure decibels produced by original and final design when heavily shaken from 3 ft away	57% noise reduction	Pass
7	Number of 3D printed parts must be greater than one	Zero 3D printed parts	N/A	Ten 3D printed parts	Pass
8	New shields must have a better appearance and fit in the vehicle than the original	N/A	Survey the ASME club about their approval of the new design	100% approval	Pass

8.2 Appendix B: Failure Modes and Effects Analysis (FMEA)

Team Number: 003		Team Name: ASME Shell Eco-Marathon					Date: December 4, 2022			
Part Title and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Shield mount Secures tire shields to axle mount	Bolt fully fractures	No longer is secured to axle	6	Defect in bolt lowering load capacity	1	Check FEA and visual inspection	2	12	Upgrade bolt
	Mount translates from original spot	Changes location of shield	3	Clamp is not tightened enough	6	Check FEA and visual inspection	1	18	Increase clamping, change geometry
	Heat set insert detaches from mount	No longer is secured to axle	6	Insert not properly heated when installed or hole is too large	3	Check FEA and visual inspection	3	**54**	Fix hole size
	Mounting plate deforms	Changes mounting location and mounting strength	3	High forces from shield in any direction	4	Check FEA and visual inspection	5	**60**	Strengthen mount, geometry change
	Bolt deforms	Changes mounting location and mounting strength	3	High shear forces from clamp	1	Check FEA and visual inspection	5	15	Upgrade bolt
	Mounting plate fully fractures	No longer is secured to axle	7	High forces from the shield in any direction. Defect in 3D print	3	Check FEA and visual inspection	1	21	Strengthen mount, geometry change
	Mount delaminates	Looses connection between shield and axle	7	Poor 3D printing process	3	Check FEA and visual inspection	2	**42**	Reprint
	Mount sleeve fully fractures	Reduced mounting strength significantly	6	High forces from the shield in any direction. Defect in 3D print. Driver impacts mount	2	Check FEA and visual inspection	1	12	Strengthen mount, geometry change
	Mount sleeve deforms	Reduced mounting strength and location	4	High forces from the shield in any direction. Defect in 3D print. Driver impacts mount	6	Check FEA and visual inspection	3	**72**	Strengthen mount, geometry change

	Mounting threads strip	No longer is secured to axle	6	High clamping forces and repeated use	3	Check FEA and visual inspectio n	5	**90**	Upgrade bolt and insert
Tire shields Act as a barrier between the tires and driver	Curved edge clips deform	Curved edges no longer connect	1	Too forceful when clipping together	7	Visual inspectio n	2	14	Redesign geometry
	Curved edges detach from main plate	Curved edges collide with tires	7	Epoxy degradation	6	Visual inspectio n	1	**42**	Use stronger epoxy/design more surface area connection point
	Curved edges delaminate	Edges more prone to breakage	1	Poor 3D printing process	4	Visual inspectio n	2	8	Reprint
	Carbon fiber rods detach from main plate	Additional support removed and rods collide with tires	7	Epoxy degradation	7	Visual inspectio n	1	**49**	Use stronger epoxy/design more surface area connection point
	Curved edges deform	Connection points no longer hold true	1	Extreme heat	3	Visual inspectio n	2	6	Redesign geometry
	Curved edges fully fracture	Curved edges collide with tires	7	Collision while driving	2	Visual inspectio n	1	14	Strengthen design/geometr y change
	Main plate deforms	Uglier appearance and reduced structural integrity	1	Extreme heat	1	Visual inspectio n	1	1	Change material
	Main plate detaches from mount	Tire shields no longer attached	6	Epoxy degradation	4	Visual inspectio n	1	**24**	Use stronger epoxy/design more surface area connection point
	Carbon fiber rods fully fractures	Shields lose rigidity	1	Collision while driving	2	Visual inspectio n	1	2	Change geometry
	Main plate fully fractures	Debris can enter vehicle	3	Collision while driving	1	Visual inspectio n	1	3	Change material
Axle mount Secures the steering assembl	Arms deform	Camber angle changes	6	High input force from driver	1	Check FEA, visual inspectio n	2	12	Design CAD with FOS of 3

y to the vehicle									
	Base plate detaches from chassis	Wheels and steering inoperable	10	High input force from driver	1	Check FEA, visual inspection	2	20	Design CAD with FOS of 3
	Base plate deforms	Wheels and steering function poorly	7	High input force from driver	1	Check FEA, visual inspection	2	14	Design CAD with FOS of 3
	Axle mount detaches from base plate	Wheels and steering inoperable	10	Poor welded connection	3	Visual inspection	7	**210**	Find skilled aluminum welder, create connection points where stress is low
	Arms fully fracture	Wheels and steering no longer attached	10	High input force from driver	1	Check FEA, visual inspection	2	20	Design CAD with FOS of 3
	Caster angle deforms	Caster angle changes	4	Poor welded connection	3	Visual inspection	7	**84**	Find skilled aluminum welder, create connection points where stress is low
	King pin holes deform	Difficulty steering	5	High input force from driver	1	Check FEA, visual inspection	2	10	Design CAD with FOS of 3
	King pin holes fully fracture	Difficulty steering	7	High input force from driver	1	Check FEA, visual inspection	2	14	Design CAD with FOS of 3
	King pin mount deforms	Camber angle changes	6	High input force from driver	1	Check FEA, visual inspection	2	12	Design CAD with FOS of 3
	King pin mount fully fractures	Wheels and steering inoperable	10	High input force from driver	1	Check FEA, visual inspection	2	20	Design CAD with FOS of 3
Steering arm Directs tires to desired location	Mounting location deforms	Changes steering geometry and steering arm strength	5	High input force from the driver, material defect	3	Check FEA and visual inspection	2	10	Design CAD with FOS of 3

	Tube fully fractures	Complete loss of steering control	10	High input force from the driver, material defect in tube	1	Check FEA and visual inspection	2	13	Design CAD with FOS of 4
	Tube deforms via torsion	Looses tube strength and changes geometry	6	High input force from the driver, material defect in tube	1	Check FEA and visual inspection	2	9	Design CAD with FOS of 5
	Detaches at welding point	Complete loss of steering control	10	High input force from the driver, improper weld	1	Check FEA and visual inspection	2	13	Find skilled aluminum welder, create connection points where stress is low
	Welding angle deforms	Welds loose strength and changes geometry	4	High input force from the driver, improper weld	4	Check FEA and visual inspection	2	10	Find skilled aluminum welder, create connection points where stress is low
	Mounting location fully fractures	Complete loss of steering control	10	High input force from the driver, material defect	1	Check FEA and visual inspection	2	13	Design CAD with FOS of 5
	Tube deforms via shear	Looses tube strength and changes geometry	5	High input force from the driver, material defect in tube	2	Check FEA and visual inspection	2	9	Design CAD with FOS of 6
	Handle is sharp	Driver is injured	4	Constant abrasion to handle surface. No finishing after tube manufacturing	3	Check FEA and visual inspection	2	9	Add a cover or object to reduce sharpness
	3D printed adapter fully fractures	Complete loss of steering control	10	High input force from the driver, material defect in the 3D print	3	Check FEA and visual inspection	2	15	Design CAD with FOS of 6
	3D printed adapter deforms	3D printed parts strength is reduced and changes geometry	5	High input force from the driver, material defect in the 3D print	4	Check FEA and visual inspection	2	11	Design CAD with FOS of 6

8.3 Appendix C: Bill of Materials

#	Part Number (for drawings)	Name	Description	Quantity	Source	Price Per ($)
1	ECO-400-008	Shield Faces	1/16 ABS sheets	2	McMasterCarr	32.64
2	ECO-400-001 and 002	Shield Mounts	3D printed mounts for both tire sheilds	2	HP Inc	0
3		Shield Rods	Carbon Fiber rods used to reinforce the tire sheilds	1	Amazon	12.95
4		Epoxy #1	Connects several parts of the assembly together	1	Amazon	7.36
		Epoxy #2	Connects several parts of the assembly together	1	Amazon	6.54
5		M4-35 bolts	Screws for the shield mounts	4	In house	0
6		M4 insert	Heat set insert for the mounting screws	1	Amazon	11.99
7	ECO-400-003 thru 007	Shield Edges	3D printed edges for the flat part of the tire shields	8	HP Inc	0
8		~~Steering tube~~	~~Alumumun tubes for new steering arm, that will be welded in house~~	~~1~~	~~0~~	~~0~~
9		Steering tube adapter	3D printed adapter to mate steel with aluminum	1	HP Inc	0
10		M3x0.5-30 bolts	To connect 3D printed adapter two both tubes	1	In house	0
11		M3x0.5 nuts	To connect 3D printed adapter two both tubes used with bolt	1	In house	0
12		Frame Mount Front (94.5 Deg)	Mounts frame to vechicle	2	In house	0
13		Frame Mount Rear (85.5 Deg)	Mounts frame to vechicle	2	In house	0
14		Frame		1	In house	0
15		Steering Shaft	Connects kingpin bracket to frame.	2	In house	0
16		Axial Thrust Bearing	Supports axial loads on steering shaft	4	In house	0
17		Radial Thrust Bearing	Supports radial loads on steering shaft	4	In house	0
18		King Pin Bracket	connects wheel to the frame, defines the kingpin angle	2	In house	0
19		Wheel retaining nut		2	In house	0
20		Bolt mounting	1/4-28 bolts Connects frame to mounting bracket	4	In house	0
21		Steering Rod Assembly	Attached to kingpin bracket and able the driver to steer	1	In house	0
22		Rod End Bolt	Connects tie rod to kingpin brackets	2	In house	0
23		Tie Rod	Defines ackerman arm distances	1	In house	0
24	ECO-300-001	New Frame	Designed Frame (Not Manufactured)	1	-	-
25	ECO-300-002	New Base Plate	Designed Frame (Not Manufactured)	1	-	-
					Total:	104.12