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Finite Element Analysis of a FSAE Electric Vehicle Suspension Upright

Grace K. Liverett

Jarrod A. Webber

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by

Grace K. Liverett & Jarrod A. Webber

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Honors Capstone Director: Dr. Nicholas Ginga

Assistant Professor of Mechanical & Aerospace Engineering

Grace Liverett 4/28/2023
Student (signature) Date

Jarrod Webber 4/28/23
Student (signature) Date

4/28/2023
Director (signature) Date

D. Keith Hollingsworth 4/28/2023
Department Chair (signature) Date

William S Wilkerson Digitally signed by William S Wilkerson
Date: 2023.04.28 14:12:16 -05'00'
Honors College Dean (signature) Date

Honors College
Frank Franz Hall
+1 (256) 824-6450 (voice)
+1 (256) 824-7339 (fax)
honors@uah.edu

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Grace K. Liverett

Student Name (printed)

Grace Liverett

Student Signature

4/28/2023

Date

Jarrod A. Webber

Student Name (printed)

Jarrod Webber

Student Signature

4/28/23

Date

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Abstract

Electric vehicles are a rapidly growing field of the auto industry and modern technology. At The University of Alabama in Huntsville, our senior design class has been working together to design and build a single seat electric race car based on the rules and regulations of the annual Formula Society of Automotive Engineers (FSAE) competition. The suspension team this year has been tasked with designing and manufacturing a functioning suspension assembly that integrates with the car's other subsystems including chassis, powertrain, and brakes. A portion of the suspension team's efforts are dedicated to the design and validation of the front uprights which contain the wheel bearing and serve as the attachment point for the suspension A-arms, pushrods, and brakes. In this project, several upright designs will be created and analyzed utilizing Finite Element Analysis (FEA) and basic engineering principles to optimize the weight, strength, and attachment methods for the suspension geometry members. These attachment methods will be investigated considering manufacturability, cost, and strength of the attachment. The project will create a suspension upright design that has low unsprung mass and minimal deformation while providing information for the current and future upright designs on the manufacturability and strength of the strategies to connect and mount components to the upright.

Introduction

I. Formula SAE Background

The idea for a student-led competition comparable to SAE's previous "Mini-Indy" competitions came about in the early months of 1980 [1]. The first competition was in 1981 with only four teams competing in four dynamic events and two static events [1]. The FSAE competition evolved from then to include more rules, events, competition types, and attendance. In 1982, more regulations were added to the rules including the requirement of four-wheel suspension [1]. Another major change came about in 2013 when FSAE implemented a battery electric competition in addition to the internal combustion engine competitions [2]. In 2013, out of 20 vehicle entries, only 5 teams competed and received scores in the electric vehicle category of the competition [3]. Since then, the electric portion of the FSAE competition has grown to include 43 vehicles in 2022 that competed and received a score [4].

Based on the version 2.0 Formula SAE 2023 Rules, SAE International specifies that teams must consider the Engineering Design Process to design and fabricate a small formula style vehicle to compete against other team's vehicles [5]. The FSAE Rules expect that teams will be ethical and comply with good engineering practices. In the FSAE Rules document, there are an abundance of rules described but the most applicable ones are as follows. For the suspension specific rules, every vehicle must have a front and rear suspension with shock absorbers with minimum wheel travel of 50 mm [5]. All fasteners must be critical fasteners as defined in section T.8.2 in the 2023 Rules [5]. All spherical rod ends used in the suspension design must be mounted in double shear and captured with a bolt/washer with an outer diameter that is larger than the rod end's mounting element [5].

The Formula SAE competition includes both Static and Dynamic events. These events are designed to quantify the performance of each vehicle compared to the other competing vehicles. The static events with their point distribution are depicted in Table 1. The presentation event evaluates a team's ability to present their team's information based on a concept provided prior to the competition [5]. The cost and manufacturing event assesses each team's ability to budget and make conscious monetary decisions to maximize production and cost efficiency [5]. The design event analyzes the overall engineering effort to maximize performance and reach design goals [5].

Table 1. General Static Events [5]

Static Events	Points
Presentation Event	75
Cost and Manufacturing Event	100
Design Event	150
Total	325

The dynamic events with the maximum points possible are shown in Table 2. Each of these events may include multiple runs with different drivers and specific equations to calculate the score with time corrections and error deductions (i.e. hitting cones, off course, incorrect laps) included. The acceleration event is a 75 meter course where teams are expected to complete four runs, where the scoring is based on the time it takes to get from the starting line to the finish line [5]. The suspension is tested in all of the dynamic events, but the event specifically designed to test the vehicle's cornering ability is the Skidpad event. The skidpad is a figure eight course

where the vehicle is under a constant turning condition as shown in Figure 1. The autocross event is designed to test a vehicle's handling on a narrow course that includes a variety of elements some of the most common being straights, constant turns, hairpin turns, slaloms, etc [5]. The endurance event tests a vehicle's ability to run reliably and for long durations. The efficiency event is based on the energy usage in the endurance event for electric vehicles.

Table 2. General Dynamic Events [5]

Dynamic Events	Points
Acceleration Event	100
Skid Pad Event	75
Autocross Event	125
Efficiency	100
Endurance	275
Total	675

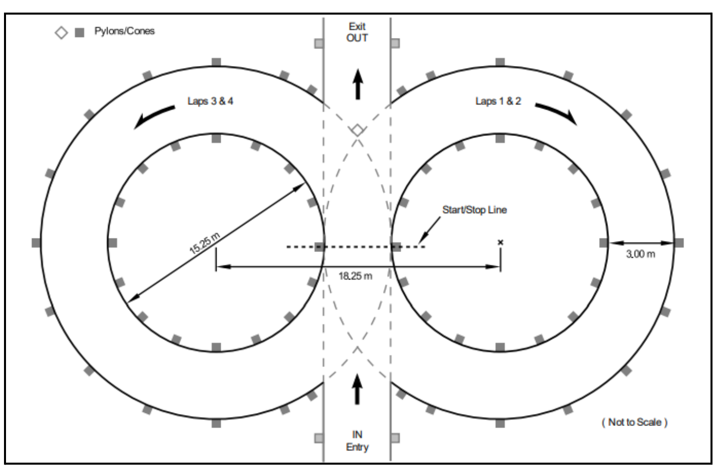

Figure 1. Skidpad Course [5]

II. Suspension Design Background

The suspension subsystem connects the wheel assembly to the rest of the chassis. The main components include the shock, rocker/bellcrank, pushrod or pullrod, A-arms, and upright; these components are displayed in Figure 2a, while an up close picture of an upright is displayed in Figure 2b. The main goal of this entire subsystem is to minimize the forces the chassis experiences and maximize tire traction in situations that it may encounter on the road or during competition events.

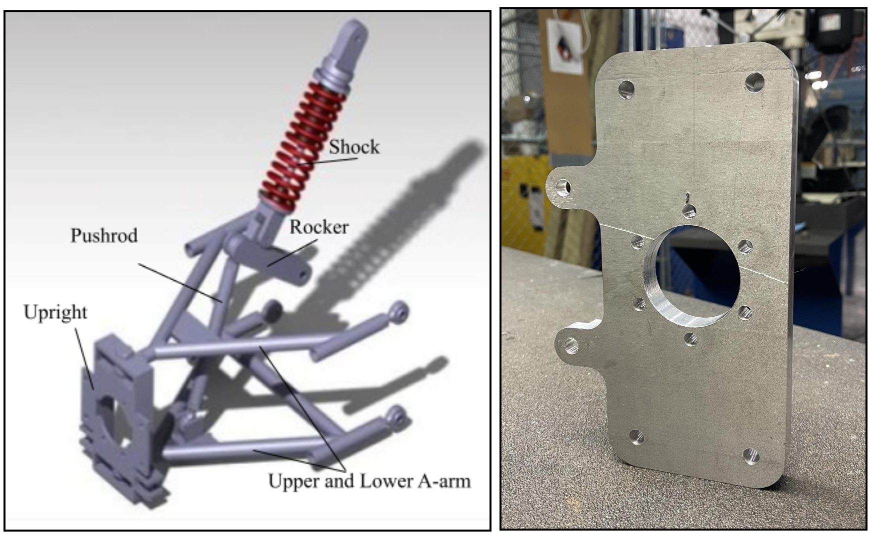

Figure 2a and 2b. (Left) General Suspension Component Assembly [6] and (Right) Upright

As such, uprights are developmentally complex to design correctly. In a rear wheel drive car architecture, such as the one in the analyzed FSAE vehicle, the front uprights serve as a connection point. For example, the vehicle’s wheels are bolted to wheel hubs, which are connected to the upright. Then the vehicle’s brake system is bolted to the upright, along with the steering toe that dictates the wheel’s angle of travel. And last, but not least, the upright must be attached to the chassis via the A-arms. Amongst these integrations, the uprights must fit within

the wheel rim diameter to prevent interference, but also allow for connection points for all the aforementioned components too. The vehicle must also be agile, easy to maneuver, and exhibit predictable driving characteristics— to which the upright design can dictate. Incorrectly dimensioned mounting locations for the brake calipers, wheel hubs, steering toes, and/or A-arms can lead to catastrophic failure and unpredictable driving dynamics; a winning FSAE team looks to avoid both of these scenarios in an upright design.

Part of designing an optimal upright includes the material choice. FSAE teams look to reduce unsprung mass, material brittleness, manufacturing complexity, and costs while maximizing material rigidity when deciding; since the upright serves as the suspension's main connection point for numerous components.. On the opposing end of the spectrum, a less rigid material can deform and potentially interfere with the wheel rim or other components after experiencing the same high magnitude forces. With this in mind, a material attribute balancing act is in order to create an optimal upright design.

Speaking of an optimal upright design, this thesis' upright design and analysis was performed based on the 2022-2023 UAH Electric Vehicle Senior Design class suspension team's design. This design used components from a previous FSAE Internal Combustion Engine (ICE) Vehicle that was located in the UAH machine shop. These components include a 120-4060 Wilwood brake caliper, custom rotor, a wheel hub, a rim insert with the rim's bolt pattern, a 43164 Hoosier tire, and a steering toe as pictured in Figures 3 - 7. The steering toe integration differs depending on the upright design, in which an upright that utilizes bolt-on brackets can integrate the toe into a bracket. Otherwise, an upright design that integrates the brackets into the upright itself would require the toe depicted in Figure 7; this difference is further depicted in the methodology section.

Figure 3. IC Car Brake Caliper

Figure 4. IC Car Wheel Hub and Rotor Assembly

Figure 5. IC Car Wheel Rim Insert

Figure 6. Hoosier Tire

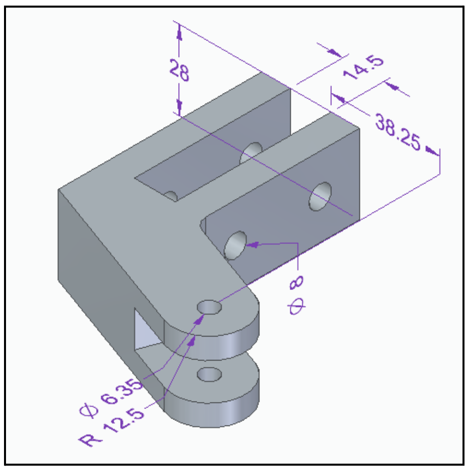

Figure 7. Steering Toe

Design Considerations and Methodology

I. Literature Review: Race Car Design

The majority of the upright design and analysis was completed based on the models in the *Race Car Design* by Derek Seward. This book was written with the intention for FSAE teams to use it as guidance for designing a FSAE vehicle's major components including the chassis frame, suspension, steering, brakes, transmission, etc [7]. Amongst the suspension analysis, chapter 6.5 pages 169 and 174 discuss upright design and analysis. This specific analysis is for the maximum cornering and maximum braking an upright will experience, including the equations necessary to calculate these forces [7]. The forces for these scenarios are shown in Figure 8 and Figure 9. The cornering analysis was described to be an assessment of the loads between the road and tire. With this assessment, the upper and lower connection points should be constrained, but be allowed to rotate as the A-arms will be permitted to rotate due to their spherical bearing. From there, the road forces will transfer from the tire to the upright via the wheel bearing/hub [7].

The book recommends the following equations for the maximum cornering scenario:

$$F_{outer} = \frac{(W_{lat} \times R_r) - (W_{vert} \times (l_1 + l_2)}{l_1} \qquad \text{(Equation 1)}$$

$$F_{inner} = F_{outer} + W_{vert} \qquad \text{(Equation 2)}$$

Equation 1 is the moment of all of the forces in the cornering scenario about the inner bearing, while Equation 2 is the summation of the vertical forces [7].

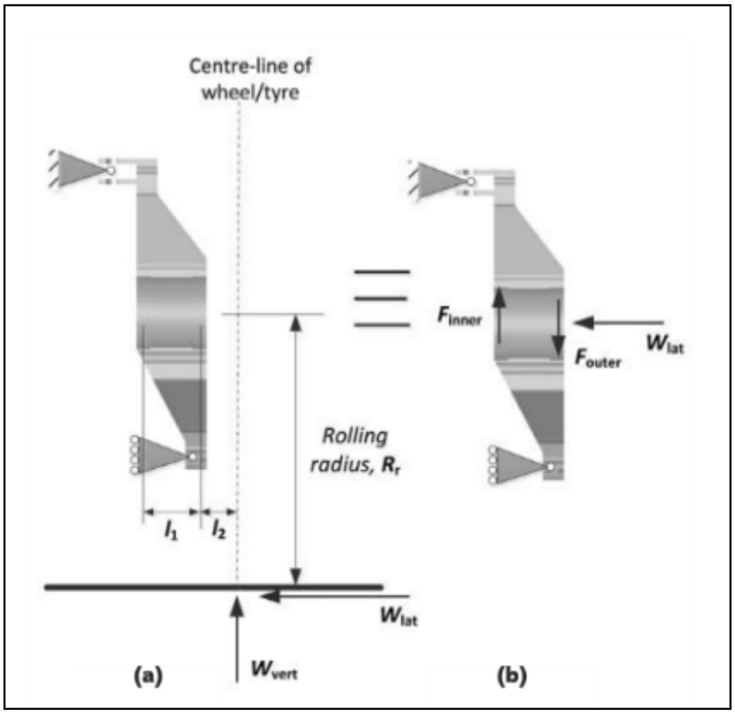

Figure 8. Force Calculations for Maximum Cornering [7]

Subsequently, while utilizing the same constraints on the upper and lower connection points, the maximum braking load equations are as follows [7]:

The moments of the center of the inner bearing (Shown in Figure 9).

$$V_{outer} = \frac{W_{vert} \times (l_1 + l_2)}{l_1} \quad \text{(Equation 3)}$$

$$H_{outer} = \frac{W_{long} \times (l_1 + l_2)}{l_1} \quad \text{(Equation 4)}$$

Summation of the vertical forces:

$$V_{inner} = V_{outer} - W_{vert} \quad \text{(Equation 5)}$$

Summation of the horizontal forces:

$$H_{inner} = H_{outer} - W_{long} \quad \text{(Equation 6)}$$

Forces acting on the center of the area on the brake pad:

$$F_{brake} = \frac{W_{long} \times R_r}{(l_3 + l_4)} \quad \text{(Equation 7)}$$

Lug forces:

$$V_{brake} = \frac{F_{brake}}{2} \quad \text{(Equation 8)}$$

Moment caused by the center of the pad:

$$H_{brake} = \frac{F_{brake} \times l_4}{l_5} \quad \text{(Equation 9)}$$

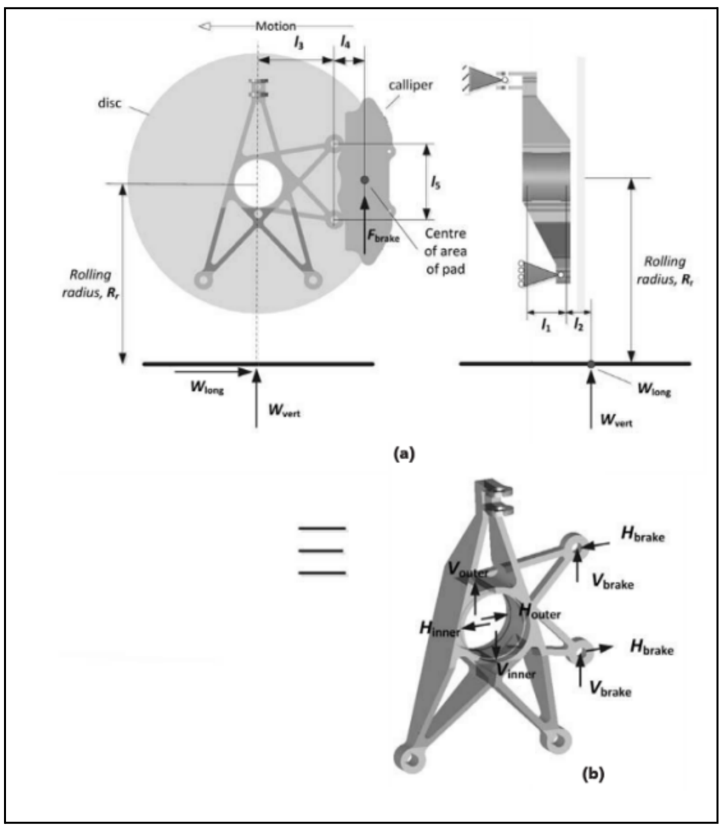

Figure 9. Force Calculations for Maximum Braking [7]

The variables required from the above equations were approximated based on the 2022-2023 Electric Vehicle Senior Design Class's designs. As such, all of the values for the variables listed in Equations 1-9 are shown in Table 3.

Table 3. Variable Values for Force Calculations

Variable	Value	Unit
W_{lat}	3161.44	N
R_r	266.7	mm
W_{vert}	2634.54	N
l_1	83.64	mm
l_2	8.09	mm
l_3	76.78	mm
l_4	28.88	mm
l_5	95.40	mm

In designing the upright, *Race Car Design* recommends a Factor of Safety (FOS) of 1.6 for critical suspension components [7]. For the purpose of this analysis, an FOS of 2 will be used based on equation 10. This is in part due to the models and FEA completed are approximations, and due to the fact that the individuals completing the analysis have minimal experience in FSAE component design.

Factor of Safety:

$$FOS = \frac{Yield\ Stress}{Max\ Stress} \quad \text{(Equation 10)}$$

II. Design For Manufacturing and Assembly (DFMA)

A key aspect of designing any part that will be manufactured or assembled is to consider what the manufacturing process and assembly process will entail. The DFMA process has the objective of reducing costs and improving quality, much akin to the purpose of this analysis. Some major objectives of DFMA include reducing overall part count, standardizing components, utilizing common parts, standardizing design features, creating an overall simplistic design, focusing on the ease of fabrication, avoiding tight tolerances, and minimizing secondary/finishing operations [8]. These key principles were utilized in the overall design and analysis of the front upright.

III. Utilized Programs

In order to design the models used in each iteration of the upright, the program Solid Edge CAD was utilized. Once models were designed in Solid Edge, they were then analyzed in the finite element analysis (FEA) simulation software included in the Solid Edge Package. This package includes a NX Nastran solver that completes the analysis once the mesh, material properties, and the boundary conditions have been defined.

IV. Utilized Machining Companies

One key aspect of this project is to minimize manufacturing costs; in doing so, four manufacturing companies were investigated. Three of which are external to UAH, but offer relatively low costs for the machining of the upright. These external options are manufacturing companies called Fictiv [9], Protolabs [10], and Xometry [11]. The fourth option was to order

stock from McMaster-Carr and machine the upright at UAH [12]. All design iterations were submitted to these companies for quotes.

Though the McMaster-Carr and UAH machine shop option is by far the least expensive, there are other sacrifices that must be made. It requires the machine shop's manager to fit the machining of this part into their schedule, so what is gained in lower costs is lost in the timeliness of the part's completion. However, it is possible that the Shop Manager does not have an abundance of parts to CNC, so the part may be done immediately.

V. Material Selection

Since one aspect of designing an upright is to minimize the unsprung mass and maximize the strength so it can withstand the multitude of forces it will experience, most FSAE uprights are manufactured from an aluminum alloy [7]. For the purposes of this report, two aluminum alloys were investigated. In the end, a selection was made based on the cost and overall strength; it came down to 6061 aluminum and 7075 aluminum as both are lightweight and strong. The important factors are listed in Table 4. Though *Race Car Design* recommends the upright to be made of a quality aluminum such as 7075-T6, the material selected here was 6061-T651 Aluminum. This is due to the lower cost, since overall budget was a critical consideration in the decision making process.

Table 4. Aluminum Selection [12]

Material	Yield Stress (MPa)	Price
6061	276	$89.97
7075	500	$150.11

VI. Forces

In completing the FEA for the upright design, the same forces and constraints are utilized across all design iterations and bracketing methods. These forces are determined based on the equations given in *I. Literature Review: Race Car Design*, and are summarized in Table 5 below; the equations utilized are shown in the table, along with the direction of the forces. For the forces, their directionality is based on the axes given in Figures 10 and 11, and each force is evenly distributed across the indicated bolt openings on the upright. For the constraints, these values are given in terms of the available six degrees of freedom, where zero indicates a locked constraint in the given direction and a lack of a value indicates no constraint (i.e, free). As a reference, the first three numerical values are for the translational axes (X, Y, and Z respectively) while the last three values are for the rotational axes (X, Y, and Z respectively).

To supplement the table, two accompanying diagrams are provided to further illustrate what forces and constraints are applied, where Figure 10 is for the bolt-on bracket design, and Figure 11 is for the integrated bracket design. In these diagrams, blue indicators represent constraints while red indicators represent forces, and each differing force is noted as a new indicator in Table 5 and on Figures 10 and 11. All forces and constraints are applied to the interior faces of the upright's bolt openings.

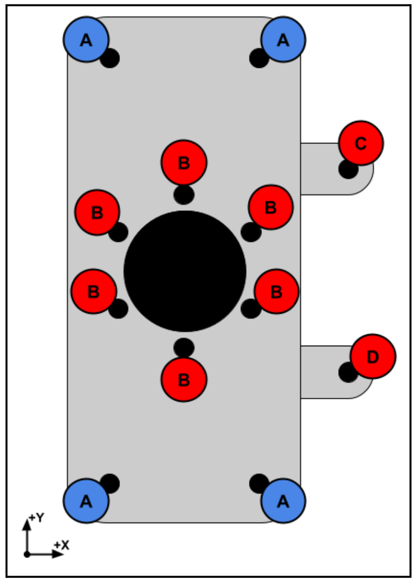

Figure 10. Bolt-On Bracket Force Diagram

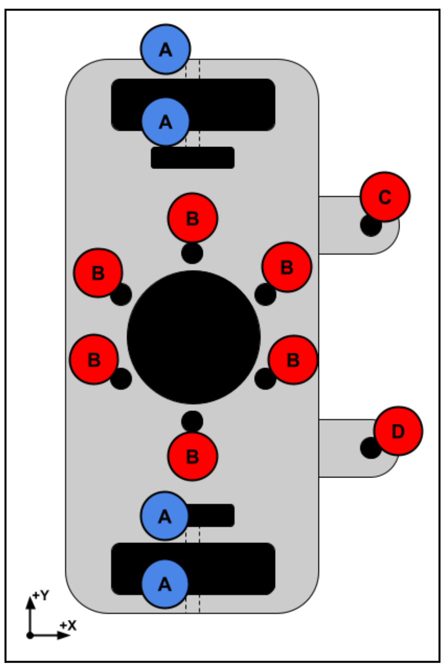

Figure 11. Integrated Bracket Force Diagram

Table 5. Force Diagrams Constraints and Forces Table

Indicator	Force or Constraint?	Constraint Directions	Force Direction	Force Magnitude (N)	Force Equation(s)
A	Constraint	< 0, 0, 0 > < 0, 0, 0 >	N/A	N/A	N/A
B	Force	N/A	+X	1,672.78	H_{outer}
			-X	147.48	H_{inner}
			+Y	12,715.32	$V_{outer} + F_{inner}$
			-Y	7,446.25	$V_{inner} + F_{outer}$
C	Force	N/A	-X	582.71	$\frac{H_{brake}}{2}$
			+Y	1,924.95	V_{brake}
D	Force	N/A	+X	582.71	$\frac{H_{brake}}{2}$
			+Y	1,924.95	V_{brake}

VII. Bolt-On Bracket vs. Integrated Bracket Upright Design

The current suspension design includes a set of brackets that allow the upright to integrate with the A-arms. The purpose of this section is to investigate if an integrated bracket design approach for the upright creates a better upright design than an upright with a bolt-on bracket design. The versions of these models are both numbered as one, but the first one is labeled as bolt-on bracket— this is the design that will use an external bracket that is bolted onto the upright (Figure 12). The other model is denoted as integrated, and it has a bracket integrated into the geometry of the upright (Figure 13).

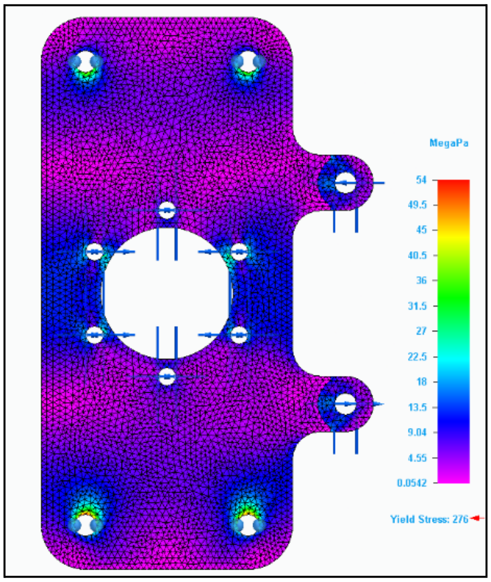

Figure 12. Bolt-On Bracket Version One FEA Results Display

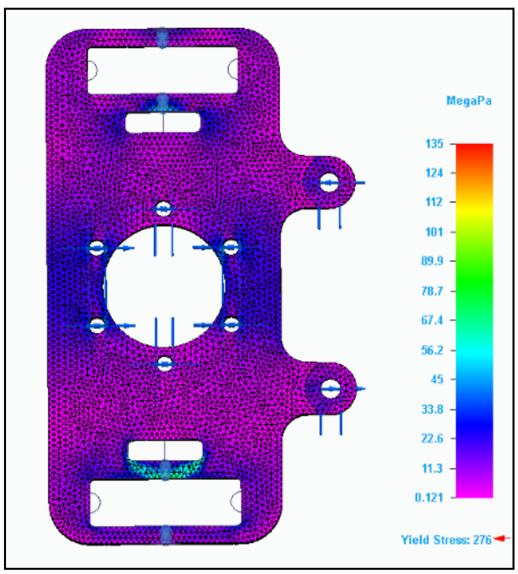

Figure 13. Integrated Bracket Version One FEA Results Display

Table 6. Bracket vs. Integrated FEA Results

Version 1	Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
Bolt-on Bracket	1.21	276	54	0.045	5.11
Integrated Bracket	1.022	276	135	0.103	2.04

Table 7. Version 1 Manufacturing Costs Table

Vendor	Total Cost Bolt-on Bracket	Total Cost Integrated Bracket
Fictiv	**$465.06**	**$326.85**
Protolabs	**$673.57**	**$577.98**
Xometry	**$441.96**	**$305.25**
McMaster-Carr	**$107.90**	**$107.90**

As displayed in the above table, Table 6, the integrated bracket version experiences higher stresses and is already at the desired FOS; thus, this bracket design is not chosen. This FOS means minimal material, if any, can be removed from the upright even though the upright version is still above 1 kg at 1.022 kg. Though the integrated version does exhibit some aspects of DFMA since it reduces the overall part count, the upright itself does not exhibit the other desired design qualities like maximizing the FOS to a minimized mass. Even though the overall cost of manufacturing for the bolt-on version is higher across the selected vendors (except McMaster-Carr) as shown in Table 7, this design can be refined to hit the analysis' 2.0 FOS at a minimized mass.

Results

I. Design Version 1

For version one, this design was meant to integrate all the design considerations given with the suspension team's components (rim sizing, brake caliper, wheel hub, wheel bearing, etc.). The results of this FEA analysis with 6061 Aluminum and the constraints and forces from the *VI. Forces* section are displayed below in Figure 14. To reiterate the forces and constraints, each version's analysis is meant to replicate a combined maximum cornering and braking load. The bracket mounting points at each model's upper and lower sections have fixed constraints, while combined cornering and braking forces are applied to the interior openings of the central bolt pattern. Specific braking forces from the brake calipers are also applied to the caliper's mounting points on the right side of each upright model.

Table 8 depicts the resultant mass, yield stress, max von Mises stress, displacement, and factor of safety (FOS), while Table 9 represents the cost to manufacture the upright version at Frictiv, Protolabs, and Xometry.

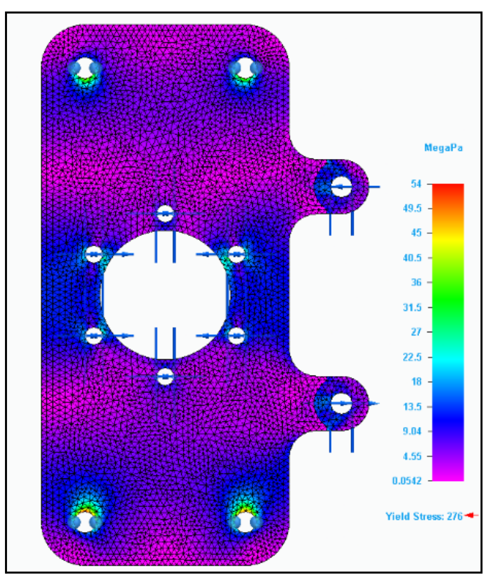

Figure 14. Version 1 FEA Results Display

Table 8. Version 1 FEA Results Table

Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
1.21	276	54	0.045	5.11

Table 9. Version 1 Manufacturing Costs Table

Vendor	Price	Shipping	Total Cost
Fictiv	$285.58	$14.28	**$326.85**
Protolabs	$492.97	$37.29	**$577.98**
Xometry	$280.05	$0.00	**$305.25**

II. Design Version 2

After analyzing version one, the upright can have its mass significantly reduced based on the FOS. Doing so results in creating spindle supports for the mounting points of the brackets and brake caliper; this is depicted in Figure 15. Table 10 displays the FEA results while Table 11 reflects the manufacturing costs from the vendors listed in the methodology section.

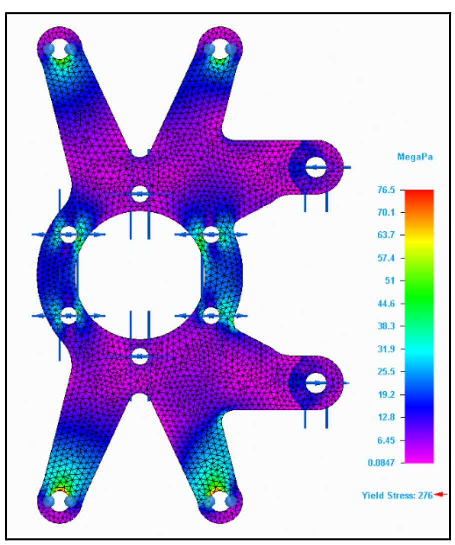

Figure 15. Version 2 FEA Results Display

Table 10. Version 2 FEA Results Table

Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
0.638	276	76.5	0.100	3.61

Table 11. Version 2 Manufacturing Costs Table

Vendor	Price	Shipping	Total Cost
Fictiv	$277.57	$14.28	**$318.12**
Protolabs	$487.84	$37.29	**$572.39**
Xometry	$369.60	$0.00	**$402.86**

III. Design Version 3

Version two's FOS reflects that even further material reduction can be performed. In doing so, the spindle geometries are altered to allow for 7.5mm thick supporting beams between the mounting points with cutouts between the beams. Figure 16 depicts the resultant changes in the FEA analysis, while Table 12 displays the FEA's numerical results and Table 13 reflects the manufacturing costs from the three analyzed vendors.

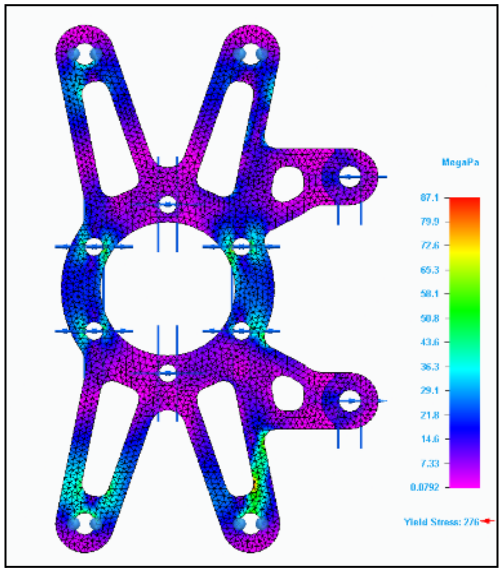

Figure 16. Version 3 FEA Results Display

Table 12. Version 3 FEA Results Table

Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
0.551	276	87.1	0.112	3.17

Table 13. Version 3 Manufacturing Costs Table

Vendor	Price	Shipping	Total Cost
Fictiv	$285.01	$14.28	**$326.23**
Protolabs	$534.78	$37.29	**$623.56**
Xometry	$430.77	$0.00	**$469.54**

IV. Design Version 4

Version three's spindle geometry change did not alter the FOS significantly, changing from 3.61 to 3.17. As such, the geometry was altered to reduce the supporting beams' thicknesses from 7.5mm to 5mm. Figure 17 depicts the resultant FEA analysis, while Table 14 returns the analysis' numerical values and Table 15 presents the manufacturing costs amongst

Fictiv, Protolabs, and Xometry. The analysis concluded here, as the FOS reached approximately 2.0— the desired FOS for the front upright.

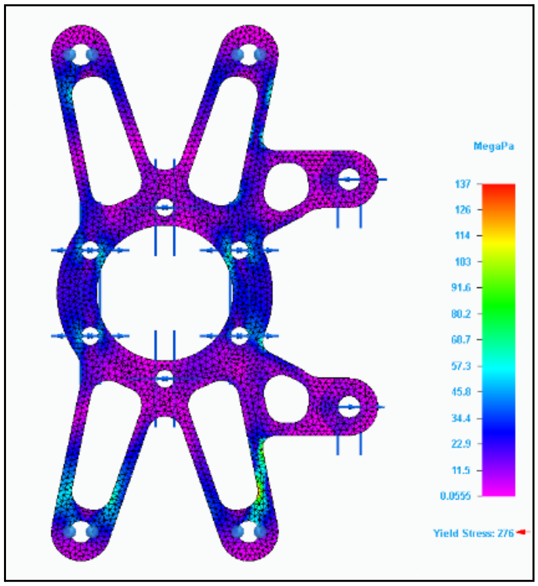

Figure 17. Version 4 FEA Results Display

Table 14. Version 4 FEA Results Table

Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
0.471	276	137	0.145	2.01

Table 15. Version 4 Manufacturing Costs Table

Vendor	Price	Shipping	Total Cost
Fictiv	$282.09	$14.28	**$323.04**
Protolabs	$507.63	$37.29	**$593.96**
Xometry	$449.59	$0.00	**$490.05**

V. Iteration Summary

Presented in Table 16 below is a summary of every iteration's FEA numerical results for quick referencing. This includes the mass, yield stress, max von Mises stress, displacement, and FOS.

Table 16. Versions 1-4 FEA Results Table

Version	Mass (kg)	Yield Stress (MPa)	Max Von Mises Stress (MPa)	Displacement (mm)	FOS
V1	1.21	276	54	0.045	5.11
V2	0.638	276	76.5	0.100	3.61
V3	0.551	276	87.1	0.112	3.17
V4	0.471	276	137	0.145	2.01

VI. Machining Costs

Akin to section *V. Iteration Summary*, this section is dedicated to providing a summary of every iteration's manufacturing costs. This includes vendors Fictiv, Protolabs, Xometry, and McMaster-Carr, which represents the UAH's machine shop being that it only requires purchasing the material. Table 17 below presents the aforementioned information.

Table 17. Versions 1-4 Manufacturing Costs Table

Version	Cost			
	Fictiv	Protolabs	Xometry	McMaster-Carr
V1	$326.85	$577.98	$305.25	$107.90
V2	$318.12	$572.39	$402.86	$107.90
V3	$326.23	$623.56	$469.54	$107.90
V4	$323.04	$593.96	$490.05	$107.90

Discussion

I. Iteration to Iteration

A. Design Version 1

Plainly stated, version one is the initial design of the upright. The design is meant to be a block of material with the necessary geometry to interface with the suspension system's numerous components. The brackets attach at the upper and lower bolt opening pairs on the upright, while the wheel hub attaches to the central bolt pattern and the wheel bearing slides into the opening. Lastly, brake calipers mount to the vertical pair of bolt openings on the right of the upright. The FEA analysis aligns with the design's expectations, being that the design yields low deformation and von Mises stress and a high FOS at 5.11. As such, the subsequent iteration is meant to be a major change.

B. Design Version 2

Version one's FOS, mass, stress, and deflection values all point to the upright being capable of a more optimized design, and thus, version two is where the design of the upright starts to develop. Each of the bracket mounting points are connected to the center bolt pattern via spindles, and any unnecessary material is immediately removed. The bracket mounting points, and central bolt pattern, have a 5mm material offset to test this design's loading results. All geometry is rounded toredice stress concentrations.

The results of this design, as seen in Figure 15, are increased stresses at the bracket mounting points and bolt pattern. These stresses still reflect a valid design however, as the FOS is 3.61, with a 0.100mm displacement— that's a 0.40 FOS difference and 0.055mm increase in deflection. The mass reduces significantly however, resulting in a 0.572 kg reduction to 0.628

kg. Based on these values however, the design can still be improved to maximize the FOS to a decreased mass.

C. Design Version 3

Version three improves on version two's design. The material offset is increased to 7.5mm around the bracket mounting points to aid in reducing stresses, while the spindles' breadth are increased. Their breadth increase allows for 7.5mm in width supports extending to the bracket mounting points, and allow for material removal between said supports. This material removal and spindle breadth increase is to reduce the total material, as most material shown in Figure 15's spindles— beyond the mounting points— has lower stress values.

Reflecting on Figure 16's version three FEA results, this increase in material offset and introduction of independent supports aid in maximizing the FOS to a minimized mass. The mass drops to 0.551kg— not as significant as version one to two, but still beneficial. The factor of safety is reduced to 3.17, with a displacement of 0.112mm. This version is meant to prove the spindle design alteration can be manipulated to achieve the desired FOS to mass outcome, which version four delivers.

D. Design Version 4

Version four is much the same as version three— independent supports for the spindles with hollowed out spindle interiors. The difference lies in the supports' thickness however, as it is reduced to 5mm; version four's FEA results reflect that stresses are still low in the spindle supports, and thus can be reduced to help meet the 2.0 FOS design goal. This design change alone returns Figure 17's FEA results.

As seen, the thickness change returns the results this analysis set out to achieve. The FOS is 2.01, while the 0.471kg mass is approximately 39% of version one's mass— a major

reduction. Deflection does increase to 0.145mm, however this value is expected and anticipated with the upright's design and intended FOS. Thus, version four is the anticipated upright design.

II. Manufacturing

Throughout the upright's design process, careful attention to DFMA has been paid to ensure the upright is easily manufacturable. The design is intended to be manufactured on a mill or CNC, meaning all potential hard edges are smoothed into curves as these machines cannot replicate hard edges. The design itself is symmetrical as well, to ensure minimal changes in the machine's programming across the workpiece, and to allow for unified bolts across suspension components. Most suspension system components utilize the same ⅜" bolt, and as such, the upright was designed with this in mind to reduce assembly headaches and variability in manufacturing.

An argument could be made that the integrated bracket upright version practices the "minimizing components" point of DFMA, however the bolt-on bracket design allows for something the integrated bracket design cannot— change. The bolt-on bracket design allows for future teams to change the design of the steering toe and A-arms connections, which this analysis deemed more important. This allows the FSAE Electric Vehicle senior design to minimize future manufacturing costs of another upright design and instead invest in manufacturing cheaper brackets and other necessary components.

As for the cost comparison amongst manufacturers (Table 17), it can be concluded that utilizing UAH's machine shop is the best option for costs across the board. Even the cheapest external online manufacturer in this trade study, Fictiv, is $215.14 more expensive than the machine shop. In relating this analysis to the 2022-2023 FSAE Electric Vehicle senior design

suspension team, the team could not have afforded externally manufacturing the uprights, even with Fictiv. The team's budget sans purchased upright stock was approximately $1899.90. If this is compared against the $2,500 budget maximum, at a $600.10 difference, this means only one of the two required uprights could be machined regardless of the external manufacturing company. Even if the team could have afforded externally machining both uprights though, the budget would better be spent on other suspension components to ensure the entire assembly is ready for chassis integration.

With this reduced costs comes a discussion on timelines however. UAH's machine shop manager only has so much time in a semester to aid in part manufacturing. Senior designs, research programs, and other facilities on campus require the manager to machine parts— even with TA's, this is a serious time dedication. Parts could take longer than expected depending on the half of the semester the drawings and stock are given to the manager; if in the first half, it should be done quickly. If part components are given in the second half though, this could take a few weeks as more people demand their time.

Compared to an external manufacturing company, they are on hard deadlines and have a definitive time the part will arrive. For example, at standard shipping speeds, Fictiv parts arrive ten days after ordering, while Protolabs parts arrive after seven days, and Xometry parts arrive after fifteen days. This should be taken into consideration when utilizing the machine shop— give drafts and stock to Jon as soon as possible in the semester. All in all however, the UAH machine shop is the recommended option due to costs. Part delivery timing should not be an issue given the necessary components are given to him early enough in the semester.

Conclusion

Designing an FSAE upright requires careful attention to detail when it comes to integration with other components, DFMA, material selection, overall design for safety, and costs. This component is meant to withstand extreme forces during an FASE competition, and as such, requires an analysis that validates the upright's abilities. The upright material, 6061-T6 Aluminum, was chosen in order to reduce costs while providing an adequate yield strength. As such, the comparison between a bolt-on bracket and integrated bracket design in this material resulted in the bolt-on bracket being the preferred design for optimizing toward a minimum FOS of 2.0 while minimizing mass.

From there, the bolt-on bracket was iterated through three spindle designs until obtaining a design with a 2.01 FOS and a mass of 0.471 kg; this is approximately a 61% decrease in mass from the original upright design. The upright design iterations were analyzed for manufacturing costs as well, resulting in the best manufacturing method being to utilize UAH's machine shop for manufacturing and McMaster-Carr for material stock purchasing. This method amounts to a $107.90 manufacturing cost— including material shipping; the next lowest cost manufacturing alternative, Fictiv, is $215.14 more in comparison. Though there are potential timeline concerns with the machine shop, getting components in early and to Jon is the best solution for prompt machining timelines.

In summary, the version-four bolt-on bracket spindle design is the best upright design to implement for future FSAE Electric Vehicle senior design needs. Including a $107.90 material cost, this design also allows for future teams to utilize the upright, as the bracketing interface is modular. This is critical in maximizing future team budgets and minimizing development time,

as the sooner component testing can begin is best for the senior design team overall. Thus, it is recommended to use the bolt-on bracket's version-four design.

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