Baja Bug Suspension | Senior Project Report

For
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Statement of Disclaimer

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Abstract

The goal of this senior project was to design and build a long travel front suspension system for a VW Bug. This started by defining the scope of the project and performing preliminary research. In this step, similar products were investigated, and research was done on stakeholders and customers. Next, concept development, design, and evaluation were performed. With this, the first iteration of our CAD model was designed, and physical prototypes were made. Using all this information, and feedback from advisors and sponsors, multiple iterations of our CAD were performed until the design was ready to manufacture. Drawings were taken from CAD and many parts were waterjet. These components were welded together and assembled to create our final design. The final design met the vertical travel specification of 17 inches but failed to meet the track width limit of 72 inches and our camber range of 0 to -5 degrees. To further improve the design, another iteration would be necessary to reduce the overall track width, slightly alter camber values, and overall improve the design.
Introduction

This report provides a final update and conclusion to the senior project of four mechanical engineering undergraduate students at California Polytechnic State University, San Luis Obispo. This document combines three earlier deliverables, with the addition of our Final Design Review (FDR). Together, these documents make up our Senior Project Report and track our design progress throughout this last year.

The first document is our Scope of Work (SOW). The SOW defines the project goal to be to design a long-travel independent front suspension system for Baja off-road racing enthusiasts to weld together and integrate on a Volkswagen Bug at a low cost. In this document, we discuss what the scope of our project will be, we do background research on stakeholders and similar products, and provide a timeline for the remainder of our project.

The next document is the preliminary design report (PDR). The PDR details concept development, design, and evaluation. This report contains the first iteration of our CAD model and goes into more detail about our design direction. The PDR also includes our initial prototypes.

Using the feedback from our PDR we altered our design in various ways. We edited our CAD (Three-Dimensional Computer Aided Design), to reflect these changes and provided detailed descriptions and drawings of all parts to be fabricated. All this information is submitted in our Critical Design Review (CDR). The CDR also outlines the justification of our design, our manufacturing plan, and our design verification plan using various tests.

Finally, in the Final Design Review (FDR), we outline how we manufactured the design and its various components. We then detail our testing procedures and comment on the success of our final design. We finish with concluding thoughts on our overall design process, what was successful and unsuccessful, and what recommendations we have for future improvement of the design.
Part I: Scope of Work

For
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Abstract
This document aims to clearly define our project, scope, and timeline for the upcoming year. First, we introduce our project and problem statement, which is to design a long travel front suspension system for a Volkswagen Bug. This means fabricating A-arms and other parts as well as specifying shocks and making the system compatible with braking and steering subsystems. We interview different stakeholders, including multiple Baja Bug owners and enthusiasts, and do extensive background research on existing solutions, patents, journal articles, and other technical literature. Then we clearly define the scope of our research using tools such as functional decomposition and quality function deployment diagrams. Finally, we state our objectives and our timeline for completion.
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1 Introduction
Our design challenge is to create a long travel off-road front suspension system for a Volkswagen Bug, in the form of an affordable do-it-yourself (DIY) kit for enthusiast mechanics. Our aim is to provide a high-performance design that is still cheap and simple enough for someone who is just entering the sport. This means that our main stakeholders are the customers and home mechanics who would be learning to design a Baja Bug and purchasing this product. This Senior Project Team is taken on by four Mechanical Engineering undergraduate students at California Polytechnic State University in San Luis Obispo: James Ankers, Rebecca Hansen, Dakota Hollingsworth, and Thomas Spycher. Dave Schlossberg, CEO of Poly Performance and Synergy Manufacturing, provides guidance from an industry perspective, and will here be referred to as the sponsor. The project coach and instructor is Professor Sarah Harding, and the funding and test-vehicle for this project is supplied by one of the students, Dakota Hollingsworth.

This document explains the project scope, beginning with relevant background research that informs the problem statement, leading into objectives, design considerations, and a progress plan for the duration of this three-quarter-long project.

2 Background
This section details our initial research as it pertains to defining the customers and their wants, how our problem has been solved before with competitive products and patents, and technical information that we expect to be relevant in our design and analysis.

2.1 Stakeholder Research
When talking to potential customers in the Baja community, we found that many enthusiasts take pride in creating something of their own and having direct, hands-on influence on the production of their equipment. This do-it-yourself approach allows enthusiasts to learn everything possible about the inner workings of their equipment, so in the case that something does break or becomes damaged in the high-paced, remote environment of Baja Racing, one can quickly diagnose and repair what needs attention. By setting up interviews with the community, we gained valuable information regarding stakeholder wants and needs in an off-road suspension system, and were also referred to several comparable products that are currently on the market today. Because the customer and consumer will also be the manufacturer, as we are developing a ‘DIY’ kit, one major goal is to make all of our designed parts simple and intuitive to fabricate. We will do this by using commonly available materials and off-the-shelf parts, as well as consulting industry experts and experienced student fabricators.

2.2 Competitive Products
To gain a better understanding of our system and how previous people have tackled similar problems, we found five front suspension designs for a Volkswagen Bug. Table 1 contains the name and photo of each system considered, along with our main takeaways from what we could find on their performance and other qualities. Later in the document, a Quality Function Deployment (QFD) analysis will be described to further compare these existing products.
<table>
<thead>
<tr>
<th>Name</th>
<th>Image</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Stock Volkswagen Bug Torsional Trailing Arm Suspension [1]           | ![Image](image1.jpg) | - Two front torsion bars connected to the wheels by trailing arms on each side.  
- Not enough vertical travel for off-road.  
- Can modify to increase ride height, but that isn’t comparable with a complete redesign for strength, travel, and desirable geometry. |
| Torsional Trailing Arm Suspension by Pacific Customs [2]              | ![Image](image2.jpg) | - Beam suspension design.  
- Durable build, but only 12 in. travel.  
- Expensive ($4000) with minimal assembly/fabrication by the customer.                                                                 |
| A-Arm Suspension Kit by iMohr [3]                                   | ![Image](image3.jpg) | - Double A-arm design, like what we are trying to build, for a reasonable $1800.  
- Not long travel suspension, more of a road performance focus.                                                                 |
| Long Travel Suspension Kit from Nichols Fab [4]                     | ![Image](image4.jpg) | - Double A-arm design, with performance quality that we are aiming for.  
- 19 in. of travel with 10 in. coil-overs.  
- $3100 is not a beginner-friendly investment.                                                                                  |
| Long Travel Suspension System by Dirtbio [5]                        | ![Image](image5.jpg) | - Double A-arm kit.  
- Only one product made, selling on eBay for just $1595.  
- 21 in. travel, +/- 1 in. bump steer.  
- Shock mounts are not provided, metal fabrication is required of the customer, and technical information is not documented (verbal assistance seems to be promised) – limiting the potential for higher production quantity.  
- Vertical travel assisted by wide track.                                                                                         |

We found that no single product combined durability, desirable geometry, long travel, and hands-on fabrication within a low budget. This is the niche that our solution will occupy.

2.3 Relevant Patents

In order to understand what suspensions systems have previously been developed, we found five patents of suspension related products. Four of these are suspension designs and the last one is a patent on a shock system. Further description of these patents can be found in Table 2. While some of these patents discuss systems which are similar in function to our concepts, they all cover a product with a very narrow scope, none of which address our problem or overlap our solution.
### Table 2 – Summary of patent research

<table>
<thead>
<tr>
<th>Patent</th>
<th>Image</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Off Road Suspension Front Suspension System [6]                        | ![Image](fig3a.png)       | - Double A-Arm Suspension  
- Strut Attaches to lower arm, and passes behind upper arm  
- Minimizes bump steer by setting the steering rod joint forward of the drive axle |
| Universal Wishbone Trailing Arm [7]                                    | ![Image](fig5.png)        | - Wishbone trailing arm suspension design  
- Articulated wishbone mount to adjust wheel camber                                                                                                   |
| Wishbone for Automotive Suspension [8]                                 | ![Image](fig7.png)        | - Wishbone suspension design  
- Made of sheet metal  
- Cost effective                                                                                                                                      |
| Individual Wheel Suspension of a double wishbone type [9]              | ![Image](fig9.png)        | - Shock is mounted to control arm and chassis  
- Wheels move independently                                                                                                                              |
| Adjustable Internal Bypass Shock Absorber Featuring a Fluid Flow Regulator [10] | ![Image](fig10.png)      | - Piston with fluid flow regulator  
- Independent compression and rebound dampening  
- Tapered needle controlling where shock exhibits max resistance                                                                                     |

### 2.4 Technical Research

This technical research section is intended to explain what we have learned about each major technical challenge expected in the analysis for our project, and what still needs further research. Here, we cover fundamental front suspension layouts, geometry selection, load prediction, and structural component sizing.
2.4.1 Suspension Layout Selection
The first step in our technical research was choosing a suspension layout for this application. The Volkswagen Bug comes from the factory with a very outdated trailing arm layout in the front. While this system can be modified for some off-road improvements, moving to a new layout such as MacPherson Strut (Figure 1a) or Double Wishbone (Figure 1b) can provide many advantages from a performance and packaging standpoint.

The two systems offer a similar overall function but differ significantly in operation. The primary difference between the two is the path of motion the wheel and hub travel through as the system is cycled. In the MacPherson Strut system, the wheel hub is fixed to just one ‘arm’ or beam connecting it to the chassis of the car. This means that the wheel & hub are in circular motion around the inner pinned connection of the arm, which therefore means that the angular orientation (commonly referred to as the alignment) of the wheel will vary significantly throughout the suspension’s cycle.

The Double Wishbone style system fixes the wheel hub to the chassis with two structural arms, which have pinned connections at either end. This layout allows the wheel hub to maintain a more controllable angular orientation throughout the suspensions’ cycle. The double wishbone system also makes it possible to have a much wider track width, which in turn allows the system to have longer travel, which is one of the primary engineering specifications of this project. It is for these reasons that we chose to proceed with the double wishbone style layout.

2.4.2 Geometric Considerations
In an automotive suspension system for a performance application, the static and dynamic angular orientations of the wheel directly impact how the vehicle feels to drive and how much grip is generated in various driving conditions. The primary geometric considerations are those of camber, toe, and caster. Additionally, the angular layout of each arm should be carefully tuned to achieve a desired instant center and roll center, depicted in Figure 2.
To generate maximum grip, the contact area between the tire and the ground must be maximized. For this application, we want to generate as much front tire grip during cornering as possible. This will be achieved primarily through carefully selected camber and toe alignment curves, which will keep the tire flat on the ground and thus maximize contact area. Although these alignment curves are best refined with the aid of empirical data gathered from testing, our initial alignment settings will be around -2.5° degrees of negative camber angle, which will increase as the suspension is compressed to a maximum of -4.5° of negative camber at full compression. These specifications are based on empirical testing data of normal, longitudinal, and lateral forces generated by the tire under various conditions, as measured by the Department of Vehicle Technology at John von Neumann University in Hungary [13]. It may be noted that these curves can be calculated with a numerical tool such as MATLAB [14], or output from a suspension design software such as Lotus Suspension Analysis, if our team can get a license.

One additional alignment specification that must be carefully considered is caster. Caster is an angle measurement of how much the suspension trails or leads the axis of steering. Positive caster makes the vehicle easier to control and provides directional stability, reducing its tendency to wander and creating a ‘self steering’ effect. Having a well tuned caster angle is very important to vehicle handling and performance, as large amounts of caster make steering heavy and less responsive, and not enough caster will make the vehicle difficult to control as it will want to wander from one direction to the other, as opposed to naturally returning to a centered steering angle. Our team sponsor Dave Schlossberg of Poly Performance and Synergy MFG recommended a castor angle between 4° and 6°. Until further testing can be done to provide empirical data on what caster angle will be best, we will aim for 6° of static caster.

Aside from performance concerns, we must also develop suspension geometry to allow packaging of the supplemental components of the front suspension, including but not limited to; the braking system, steering system, and the coil-over damper. Though we will not be designing these subsystems, it is vital that there is room for them to function as intended, as well as ample room to perform maintenance and repairs on each system.

In addition, it is important to consider two potentially detrimental geometric flaws, binding and bump steer. If poorly designed, a suspension’s travel could be limited by interference or bind. This can be prevented with CAD motion studies, orienting heim joints such that rods do not hit the joint casing, and sizing components to not exceed rated slopes at bearings. Bump steer occurs when the terrain input on
the wheels causes the vehicle to steer in a certain direction without any driver input. This can make a vehicle difficult to control and reduces the vehicle's handling performance. To avoid this, the tie rods and rack must be carefully mounted so that they move in the same arc as the suspension system. By matching the movement of these two components, we can be sure that neither component pulls on the other causing bump steer [15].

2.4.3 Load Prediction

In order to structurally size our designed components to not break in cyclic fatigue, we first need to determine the loads in our vehicle. Fundamentally, all intended forces originate at the tires’ contact with the ground, including traction, lateral forces for cornering, and vertical forces for the weight and vibration attenuation. For a typical passenger vehicle, vertical forces are by far the most significant [16], and are thus well studied with multi-degree of freedom models. Vertical forces are also important for rider comfort, and suspension data can even be used to identify types of motion that cause motion sickness [16]. One study was found to investigate how complex a vertical suspension model is needed for reasonable accuracy. In Figure 3, increasingly complex models from this source are compared [17].

![Figure 3 – Dynamic Suspension Models of Varying Complexity][17]

The study ends up recommending the half-car as a balance between computation and accuracy for a random road profile. However, we are only designing the front independent suspension, and want to make use of different vertical positions of the front wheels for clearing rocks and other terrain obstacles. This may lead us to a less conventional half-car model that includes the front left and right sides, rather than one front and one rear.

Unfortunately, this method of tracking the vertical motion of sprung and un-sprung masses requires precise knowledge of the spring and damping rates of any compliant parts in a suspension system, which are often difficult to categorize. This method also does not directly predict lateral forces, which can be even more significant than vertical loads for off-road vehicles [18], so such a dynamic analysis will not be the main focus of this project. To expedite any modeling we might do here, Simulink’s built-in half-car model could be used as a baseline [19].

An alternative method of defining forces is to simply assume a worst-case impact loading in terms of g’s on any given tire. One article, posted by Rochester Baja SAE regarding vehicle frame load cases, described their typical loading conditions as max impact loading of 8g’s of impact [20], and the 2015 Cal Poly SAE Baja team published similar results for maximum loads in g’s from strain gauges measured during a variety of off-road driving and terrain scenarios [21].
Since extreme terrain cases can exceed the intended suspension capacity, we can’t simply cap our structural analysis at the maximum rated spring and damper forces. In such a case, bump stops and straps are used to redirect force from coil-overs to rigid links, disrupting ride comfort but preventing damage to the expensive coil-overs. Without the ability to conduct thorough testing of our own, a compromise between the highly academic load analysis and the potential for virtually unbounded collisions is to fatigue size for the expected operating forces, and static size for a one-time higher load of 8 g’s.

Additionally, we interviewed a Cal Poly SAE Baja team member about their common practices with load modeling and modified their method for our needs. The first case is a front impact on the arm, simulating a crash from 40 mph to a complete stop. We plan to model this as a fixed connection to the chassis and apply a load at the end of the lower arm. Seeing that this would be a worst-case loading, we will design with a safety factor of two.

A second undesirable loading case we could see on the lower arm would be a jump where the bump stops reach full compression and the vehicle would land on one wheel at an angle. We could model this with pin connections at the chassis, fixed bump stop surface, and forces at the end of the arm to cause bending and axial stress conditions. Since this loading case is more common, we will use a safety factor of three for a 3g landing. Figure 4 depicts the two loading cases discussed.

Figure 4 Modeling Worst-Case Loading

2.4.4 Structural Component Design

Once the loads are known, we can move on to stress-sizing critical components. Analytical calculations are useful for straight tubes, but anything more complicated will benefit from designing with basic principals in mind with some simplified hand calculations, followed by Finite Element Analysis as verification before testing.

In our initial research, we found a topology optimizations study for lightening an A-arm [22]. Here, researchers define the algorithm’s design space from a Kinematic Envelope Analysis, a CAD simulation
motion that tracks the full range of motion of critical parts to prevent interference. Then, topology optimization uses Finite Element Analysis to whittle down the design space, removing material that is found to carry little load until the geometry is more efficient. This process is summarized below in Figure 5, from the study’s images.

![Figure 5 - Visual Summary of an A-arm Structural Topology Optimization][22]

Though part of the team has some experience with this technique, accurate results are difficult to generate. Instead, one “manual iteration” may be performed after analyzing initial FEA results if weight savings is deemed an important goal for the project.

3 Project Scope
The next step in defining the problem is to limit the scope of what systems are being designed, and what are on the boundary, or interfacing with our design. Here, we define our physical scope, all functions that we wish to enable, and all deliverables we wish to create.

3.1 Boundary Sketch
The immediate project scope is limited to the development of an independent front suspension geometry for swapping out with the stock configuration, while maintaining interface with other critical subsystems of standard sizes and configurations. These subsystems will not be designed by the team, but the solution will need to be compatible with the following:

- **Braking System**
  - Provide a flat place to put a weld-on caliper mounting bracket
- **Tie-ins**
  - Provide mounting to known geometry points on a roll cage
- **Wheel & Tire**
  - Set ground offset so the chassis doesn’t scrape the ground at max compression
- **Steering**
  - Allow space for steering column
  - Need to know rack travel envelope to eliminate binding from droop to compression

A clarifying boundary sketch is provided as Figure 6, where blue components are out of scope and included only for reference.
3.2 Functional Decomposition

Functional Decomposition is a method used here to get at the basic essence of what our product needs to do, by identifying the fundamental task and then breaking it down into parts. This analysis is a part of defining the project scope, since it limits the functionality of the solution to not have unnecessary, time-consuming features. The diagram, shown as Figure 7, asks “how” in the downward direction of information flow, and asks “why” in the reverse direction. Solutions and implementations are left out of this initial analysis. Here, we limited our scope with Function Decomposition by only considering the performance gains from a suspension swap and identifying implementations that fulfill multiple functions.
3.3 Planned Deliverables
The final deliverables are intended to be:
1. Dakota Hollingsworth’s Volkswagen Beetle with a new front suspension, ready to drive
2. Assembly instructions or video for a hands-on customer to complete the same swap
3. A plan for parts and welding fixtures that would be included in a theoretical hands-on kit
4. CAD files for the entire front suspension system

Though the marketing and distribution of actual kits is beyond the scope of our project, the intent is to provide engineering and assembly documentation for the benefit of non-engineering Baja enthusiasts and to set-up such that this option could be pursued later.

4 Objectives
With all the preparation discussed thus far, we are now ready to present a specific problem statement and quantify the desired outcomes and performance characteristics of the project.

4.1 Problem Statement
Our project seeks to provide a way for Baja Racing enthusiasts to cost-effectively enter the sport with significant suspension performance gains (over a stock set-up) in off-road races, while gaining hands-on experience and cutting costs by assembling and partially fabricating their own front suspension system on the iconic Volkswagen Bug. The system should obtain around 17 in. of vertical travel, while avoiding binding and bump steer. It should also maintain desirable camber angles throughout the entire travel.

4.2 Stakeholder Wants & Needs
We reached out to two people that both have social media platforms that revolve around Baja Bugs. The first was Doug Bug, who has a YouTube channel where he documents his process of fabricating his own long travel suspension system for a Volkswagen Beetle. The other interviewed customer was from Instagram, @Dust_buggy. They are a husband and wife duo that modified their Volkswagen Beetle for
trail riding. During both interviews we asked them what their wants and needs would be if they were looking into a long travel suspension system. One of the first things they said was that the long travel front end they bought needed to be compatible with a 3x3 trailing arm. This trailing arm is a modification that is done to the rear end of the bug that extends the wheelbase by 3 in. and increases the rear track width by 3 inches. The next thing they talked about was how much travel they would be receiving out of the kit. The desired number was around 17 in. of travel, and both defined 12 to 15 inches of travel as a mid-travel suspension.

Further, both mentioned that not everyone installs or fabricates a roll cage in the same manner so our design would have to be easy to tie into any general six-point roll cage. Both customers we interviewed also mentioned they wanted positive caster and zero bump steer within the suspension geometry. They expect that the material used would be 4130 or DOM .095 wall for tubing and 1/8 to 3/16 in. steel plate.

All the potential customer interviews echoed and expanded on the wants and needs of our immediate customer, Dakota Hollingsworth.

4.3 Quality Function Deployment

Quality Function Deployment (QFD) is a method used here to directly relate customer needs and wants to measurable specifications for use in evaluating design success. A House of Quality (HOQ) matrix, included in the Appendix, was used to define engineering specifications that directly address a customer need, determine the most critical needs and specifications, and benchmark existing solutions. Some of our specifications ended up having a binary “yes” as a target, so we have reconsidered those as design considerations rather than specifications, though they remain in the HOQ – our product should have acceptable alignment curves, qualitatively sufficient ride comfort, welding tabs, off-the-shelf parts, and assembly documentation. By using these tools to guide our design criteria we learned that the customer wants and needs in this project far out-rank the manufacturer’s needs, since their job is simple (basic plate cutting and tube bending, of which us students are capable) and they do not have relevant needs that could shift the project direction. The QFD confirmed that there is not an existing kit like we intend to create out there that met all of the customer needs.

The engineering specifications used to evaluate the success of a design are developed from the “How” and “How Much” sections of the House of Quality and are listed in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Specification</th>
<th>Target</th>
<th>Tolerance</th>
<th>Difficulty*</th>
<th>Compliance**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Track Width</td>
<td>72 in</td>
<td>± 2 in.</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>Vertical Travel</td>
<td>17 in</td>
<td>Min</td>
<td>L</td>
<td>A, I, T</td>
</tr>
<tr>
<td>3</td>
<td>Bump Steer</td>
<td>0.00in</td>
<td>± 0.03 in.</td>
<td>M</td>
<td>A, I, T</td>
</tr>
<tr>
<td>4</td>
<td>Fatigue Life</td>
<td>10^6 cycles</td>
<td>Min</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>Allowable Force</td>
<td>See Load Prediction</td>
<td>Min</td>
<td>H</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>System Cost</td>
<td>$1500</td>
<td>Max</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>7</td>
<td>System Weight</td>
<td>200 lbf</td>
<td>Max</td>
<td>M</td>
<td>A, I</td>
</tr>
</tbody>
</table>

*Difficulty of meeting specification: (H) High, (M) Medium, (L) Low

**Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

When creating our engineering specifications, we made sure to consider all customer wants and needs. First off, track width and vertical travel are easily achievable target goals for our design. Our track width
is sufficiently wide that our desired vertical travel of 17 in. is geometrically reasonable, and these specifications can simply be implemented. In addition, we want the front track width to be about as wide as the rear when using a 3x3 trailing arm system, which is common for these vehicles. This is how we obtained the value of $72 \pm 2$ in. The complexity arises when the selected geometry needs to be tuned to eliminate small angle movements over the systems travel. If this can be done, bump steer will be minimized and the vehicle will have improved handling characteristics. Our target value for this specification is $0.00 \pm 0.03$ in.

As a safety and quality concern, our designed parts must not break in operation. The loading cases we have selected to design for has been discussed in the section on load prediction. We want to size the control arms for infinite fatigue life (here, the fatigue life of steel is categorized as $10^6$ cycles) since every whoop, jump, or bump will rapidly cycle through the expected loads. As discussed, we will also develop confidence in our system’s durability by sizing for one-time worst-case loading conditions – this will be a likely conservative, easier alternative to fatigue predictions, and will be the focus of our sizing. We know that bushing and hiems are normally replaced after every race season due to abuse, so we do not plan on sizing those for infinite fatigue, as it would unnecessarily increase cost and weight.

For less technical customer needs, we are aiming to keep our total cost competitive and weight down. Our cost goal might be one of the more difficult targets to hit since we want to use strong material such as 4130 or DOM 1020/1026 and want to use shocks with sufficient capabilities and adjustment.

We want to keep weight down so the system is not unwieldy for an individual to assemble, and to improve vehicle performance from lightweighting. Finally, we want to minimize the acceleration of the sprung mass of the car. The less movement and roll we have in the cars sprung mass due to terrain input the easier it is for the driver to control the car in intense driving conditions. Some other consideration that are not specifications are to make sure there is no binding throughout the suspension travel and to make sure we design our system around parts that are essential to steering and braking.

5 Project Management

In this section, we outline how the project is intended to progress through the year. Our planned design methodology organizes team efforts to first take care of aspects of the design that other subsystems depend on, avoiding potential bottlenecks throughout the year. Our timeline establishes an understanding of how the project needs to mesh with the senior design class schedule, and the upcoming tasks section shows how the team is on track and ready for the next deliverables.

5.1 Design Process & Approach

Our team’s design process will begin with selecting the parts and systems that will be purchased rather than designed, to be selected based on performance, price, and availability for possible DIY’er to follow suit. Then, we will work in CAD, tracking the travel of all suspension components to define the kinematic envelope for our designed pieces. With geometry decided, load analysis results will be used to structurally size designed parts. Finally, we will manufacture parts and document our assembly and installation of our suspension solution for Dakota Hollingsworth’s vehicle. The team does not have a testing budget, so evaluations of the design will rely on CAD and cardboard geometry proof-of-concepts, with some stress simulation, before the final build where success will be largely pass/fail.
5.2 Timeline
Our timeline spans from late September 2021 until the deadline for final deliverables and the Mechanical Engineering Senior Project Exposition in early June 2022, filling three academic quarters. Project progress is tracked through a Gantt chart, included in as Appendix B. In summary, the project is comprised of phases of initial research, ideation, concept selection, design, analysis, prototype building, and test verification. Interspersed are deliverable deadlines and evaluations of completed work, as detailed in Table 4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
<th>Deliverables</th>
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<tr>
<td>10/20</td>
<td>Submit SOW to Sponsor</td>
<td>Initial Research, Problem Statement, QFD, Gantt</td>
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<tr>
<td></td>
<td></td>
<td>Chart, Function Decomposition</td>
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<td>11/16</td>
<td>Preliminary Design Review</td>
<td>Decision Matrix, Concept CAD, Basic Prototype</td>
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<td>01/13</td>
<td>Interim Design Review</td>
<td>Detailed CAD Progress, Refined System Models</td>
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<td>02/03</td>
<td>Review of Manufacturing Plan</td>
<td>Detail Drawings, Manufacturing Procedure Documentation</td>
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<tr>
<td>02/08</td>
<td>Critical Design Review</td>
<td>Detailed Analysis, BOM, Test Plans</td>
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<td>02/17</td>
<td>Safety Review</td>
<td>Risk Assessment, Updated Test Plans</td>
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<td>03/10</td>
<td>Review of Manufacturing and Test</td>
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<td>Testing Plans for Evaluating all Engineering</td>
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<td>05/24</td>
<td>Complete FDR Report</td>
<td>Written Report Containing Final Results</td>
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<tr>
<td>05/27</td>
<td>Senior Project Exposition</td>
<td>Final Prototype, Technical Poster</td>
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5.3 Upcoming Tasks
The next major milestone in the project is a Preliminary Design Review (PDR) on November 16. In preparation for this, we will go through multiple ideations phases to come up with numerous designs and create a Weighted Decision Matrix and to help us narrow down to our final design based on how well each design is expected to meet the specifications defined here. Concept CAD and a simple built prototype of the selected solution are then deliverables for the PDR.

6 Conclusion
In conclusion, for this project we will be designing a 17 in. vertical travel front suspension system for a Volkswagen Bug. We have carefully narrowed down the scope of our project to include only the suspension geometry and the necessary mounts to allow compatibility with braking and steering. Our goal by the end of the year is to have a fully functioning vehicle with the long travel suspension system installed, CAD files for the entire system, and necessary documentation to allow easy customer fabrication in our footsteps. From here, we will conduct ideation to define a design that best meets the specifications chosen here.

We now request our mentor, Dave Schlossberg, to accept this project proposal or provide corrective suggestions.
References


## Appendix A | House of Quality

### QFD House of Quality

**Project:** FZS - Bio-E Bug Suspension  
**Revision Date:** 1/30/2021

<p>| Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | Column 6 | Column 7 | Column 8 | Column 9 | Column 10 | Column 11 | Column 12 | Column 13 | Column 14 | Column 15 | Column 16 | Column 17 | Column 18 | Column 19 | Column 20 |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
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| Weight Chart | 10% | 8 | 5 | | | | | | | | | | | | | | | | | |
| Relative Weight | | | | | | | | | | | | | | | | | | | | | |
| DPF Customer | | | | | | | | | | | | | | | | | | | | | |
| WAQTT: Customer Requirements | | | | | | | | | | | | | | | | | | | | | |
| WAQTT: Engineering Requirements (Ways/Means) | | | | | | | | | | | | | | | | | | | | | |
| WNMC: Customer Requirements (Ways/Means) | | | | | | | | | | | | | | | | | | | | | |
| WNMC: Engineering Requirements (Ways/Means) | | | | | | | | | | | | | | | | | | | | | |
| Major Objective | | | | | | | | | | | | | | | | | | | | | |
| Mission Statement | | | | | | | | | | | | | | | | | | | | | |
| Direction of Improvement | | | | | | | | | | | | | | | | | | | | | |
| NOX: Correlation Products | | | | | | | | | | | | | | | | | | | | | |
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Part II: Preliminary Design Report

For

Dave Schlossberg at Poly Performance

Presented By

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Revised On

01/10/2022
Abstract

This report provides a progress update and design direction for the senior project of four mechanical engineering undergraduate students at California Polytechnic State University, San Luis Obispo. The document follows an earlier deliverable, the Scope of Work document (SOW), that defined the project goal to be to design a long-travel independent front suspension system for Baja off-road racing enthusiasts to weld together and integrate on a Volkswagen Bug at a low cost. Since then, we have performed concept development by creative ideation, concept selection by comparative performance analysis in Pugh and decision matrices, geometry-focused concept design by 3D CAD (Three-Dimensional Computer Aided Design), physical prototyping, and concept justification by initial verification. Our concept selection results define our design direction as an independent front suspension with a bent round-tube subframe, parallel double A-arm configuration, and a custom fabricated upright. Initial verification from our CAD and prototype confirms the feasibility of our 17 inches of vertical travel goal without bind. We also achieve an acceptable 3 degrees of negative camber gain throughout the suspension travel, and a predicted kit cost of just under our $1500 target. If these metrics are consistent in our final design, we will have successfully achieved our goal of creating a relatively inexpensive, DIY long-suspension system for the front of a Volkswagen Bug.
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1 Introduction

We begin by reminding the reader of the project goal: to provide a way for Baja Racing enthusiasts to cost-effectively enter the sport with significant suspension performance gains (over a stock set-up) in off-road races, while gaining hands-on experience and cutting costs by assembling and partially fabricating their own independent front suspension system on the iconic Volkswagen Bug. It is intended that the system obtain at least 17 inches of vertical travel, maintain desirable tire angles and alignment curves for performance, avoid mechanical failure in a 20 mph arm impact or 3g landing on one front wheel, and cost under $1500 for the DIY kit consisting of critical geometry, mounting, and joints, without coil-overs. For this project, our scope is limited to the front suspension subsystem; however, to properly design the suspension, we must also make sure it is compatible with steering and braking systems.

The recent Scope of Work deliverable was accepted by the project advisor, Professor Sarah Harding, and sponsor, Dave Schlossberg, after recommending a 4° to 6° castor angle for controllability. This would give us the benefits of a positive castor but also reduce the steering effort that would have been previously required. It was also recommended that we should incorporate a sales and marketing plan to truly bring the DIY kit concept to fruition, but this is beyond the scope of a mechanically focused senior design project. It was pointed out that heat treating could greatly improve the performance of our steel material, but the university cannot provide resources for that, and outsourcing would exceed the project budget.

Since the Scope of Work, we have obtained a tube bending software license, a generous donation by Bend-Tech, for the Tube Shark tube bending machine on campus. We also have obtained access to OptimumKinematics, a suspension design software from OptimumG, through the university Baja Racing team. These tools will expand our manufacturing and analysis capabilities for later in the project. A checking account was set-up for clear documentation of all purchased parts and gauging the project budget. Finally, an additional interview with Cal Poly Baja Racing was conducted to replace our dubious structural qualifications with those mentioned above in our restatement of the project goal.

This document describes the performed concept development, concept selection, initial design refinement, CAD, prototyping, and concept justification with initial verification results. A project management section with a timeline discussion is included, and the project sponsor is asked to accept the design selection so that the team can move on to selecting the steering system and brakes, as well as performing structural analysis of designed components based on industry-practice worst-case load scenarios.

2 Concept Development

This section describes our process for generating, comparing, and selecting ideas for our system concept, as well as what we learned along the way.

2.1 Ideation

At the start of ideation, creative brainstorming techniques were used to generate many ideas, regardless of practicality or other constraints. The team combined individual and collaborative writing and sketching methods, considering topics from possible materials and joint parts, up to tank tread or
structural spring and damping systems. One distinction that our group made early on, was that each component that makes up our system only interacts with each other in terms of packaging and mounting, and differing component form and function does not affect system level function. This helped us decide that we could forgo system level ideation and instead achieve the same goal by simply ideating each component independently. Documentation from these ideation sessions is included in Appendix A – Documentation of Ideation Sessions.

To get a better feel for our physical system and identify any unexpected complications, team members then modeled some of the more promising ideas with office-supply materials. Our three most successful models are included as Figure 1.

![Figure 1 – Ideation Model Examples]

From this exercise, we saw how the coil-over geometry is most susceptible to interference. We considered different top and bottom arm shapes to avoid such interference and realized that a shorter top A-arm benefits camber curves. We also saw that camber offsets can be equivalently set by subframe or upright pick-up points, and that axial spacers or precise locating will be important for constraining the A-arm to a single path. Even though we learned a tremendous amount from these models, we wish we were able to model the steering rack and the limit of the hiems, to analyze binding points in our design. We made sure to incorporate some of these in our large-scale concept model.

2.2 Concept Selection

To select a configuration from all our considered designs, we first broke our system into four topics that supply the basic functions to our solution. These were arm form, arm construction, subframe layout, and upright geometry. Pugh matrices (see Appendix B – Pugh Matrices) were developed for each topic, comparing each idea to a datum. The datum we chose was an existing front suspension kit from Nichols Fab [1] that we hope to be competitive with (as previously discussed in the Scope of Work). Since our components only interact with each other at their connecting points, we decided that the topics could be considered independently. Thus, the morphological matrix step (which combines compatible components into a few final system-level designs) was skipped, and our Pugh Matrices were modified into Decision Matrices (Appendix C – Decision Matrices) to take on numeric, rather than relative, performance attributes.
Figure 2 provides a summary of all components seriously considered in our comparative matrices, and the results of our concept selection. Reasoning for why each concept was chosen is discussed next.

<table>
<thead>
<tr>
<th>Arm Layout</th>
<th>Arm Form</th>
<th>Subframe</th>
<th>Upright</th>
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<td><img src="image3" alt="Subframe" /></td>
<td><img src="image4" alt="Upright" /></td>
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**Figure 2 – Overview of Component Designs Considered, Top Ideas Circled**

2.2.1 Selection Justification

Here, we discuss the reasoning that was developed from the Pugh and Decision Matrices. For the arm layout, we wanted to err on the side of negative camber variation throughout the travel path for better control and stability, but this can also lead to less vertical travel due to binding in the rack sooner. This left deciding whether to use a shorter top arm, or same length arms. We finally decided to go with a shorter top arm because of the camber curves it provides. However, since these two designs were very closely ranked in our matrices, we may choose to switch concepts once we start our CAD.

For the form and manufacturing of the arms, it was noted that the lower arm experiences higher loads, so it would benefit from the stiffness of a box construction. Meanwhile, the tube construction is cheaper, and would allow us to reduce the weight of our system where extra strength is not necessary. For these reasons, we selected the mixed geometry with a boxed lower arm, and tube upper arm. We also plan on gusseting the upper arm for added strength. However, if interference with the shocks can’t be worked around, then we can reduce the amount of gusseting in the upper arm. These concepts were
clearly defined in our Pugh and decision matrices. The boxed lower and tube upper arm system scored the best overall because it balanced the strength and weight specifications well.

For the subframe layout, which mounts the arms and shocks, and directs suspension forces into the roll cage, we considered several variables. These were the total amount and cost of materials, as well as how well the geometry provides clearance for a potential steering rack system. Manufacturing complexity did not play into our final matrix rankings, since we decided that our target audience is technically skilled and willing to put in work for the best product. Our final choice was the curved tube subframe. This subframe has the benefit of continuous tubes, which decreases the number of cuts and welds, and provides lots of room for steering rack placement.

For the upright selection, we considered both off-the-shelf and custom-fabricated parts. Our decision to consider purchasing parts came from the fact that upright geometry can often be complex and benefit from casting or more refined machining processes than what we would like to pursue. Ultimately after looking into OEM (original equipment manufacturer) uprights, we strayed away from these stock parts to cost and more importantly strength. We continuously noticed that if we wanted to put these uprights through rugged racing conditions most of these uprights would fail. We also considered the use of ball joints vs hiems in the maintenance criteria, knowing that it is harder to press out a ball joint for replacement than it is to unscrew a hiem. Since cost was a significant driver for this project, having a custom fabricated upright was our final selection. This greatly reduced the cost of the project and allowed us to make sure that we have desirable pick up points and inclination for our kit. However, after discussing this idea with our sponsor, we decided to weld the uprights ourselves. This would allow us to be certain that the uprights meet our strength and stiffness requirements, which was the main benefit of aftermarket uprights we investigated. This fully built, custom fabricated upright, would come as part of the builder’s kit.

3 Concept Design

With a selected concept, we now describe how our team refined the system details and created both a physical prototype and CAD model to visualize the design and verify feasibility. Further discussion is then provided considering preliminary manufacturing plans. Quantifiable findings from the prototype and CAD described here are found in the Concept Evaluation section.

3.1 Detail Design Description

Our system design combines the best performing component ideas from each decision matrix and is summarized in the system layout sketch of Figure 3. As shown, this design will be composed of a double A-arm geometry, with a shorter tube-and-plate upper arm, and a longer boxed lower arm. The arms will be mounted to a curved round-tube subframe that easily incorporates a skid plate and can be welded onto an arbitrary roll cage suspension as decided by the assembling user. The other end of the arms will be mounted to a custom fabricated welded plate upright that sets the static camber and provides mounting locations for the steering tie-rod and OEM hubs. This custom upright will be fabricated by us
and would not require additional welding by the user, to ensure proper alignment and strength of this component.

Figure 3 – Concept Sketch of the Selected Front Suspension System

The distance between the arm mounting points will be the same on the subframe and the upright, making the arms parallel. This is beneficial in decreasing the camber variation through the suspension travel, as well as in enabling the steering tie rod to be mounted parallel to the arms such that all three components roughly follow the same curvature, helping to minimize bump steer (steering variation caused by toe in/out induced through the suspension travel) [2]. Another important design characteristic is the slightly shortened upper arm which enables us to maintain camber between neutral and negative 4 to 6 degrees for maximum tire contact patch when cornering. This was the main reason for choosing a shorter upper arm, rather than two same length arms, the second-best choice according to our Pugh and decision matrices. In this design we also fixed the castor at positive 5 degrees to provide us with a beneficial self-centering torque, though it will increase our steering effort due to added mechanical trail.

Though decidedly out of the design scope of this project, multiple other components need to be selected for purchase to complete the front suspension. With sponsor guidance, we are considering the wheel hubs of Figure 4 for their known durability, abundant availability, low cost (around $80 each), and because they would allow us to use OEM Toyota hubs, brakes, and wheels if desired. Additionally, the 10-inch travel King Shock coil-overs with remote reservoirs (also shown in Figure 4) are intended to be purchased for our implementation, though our suspension design will be compatible with any 10-inch travel coil-over of similar or smaller diameter that the customer may select for their system. We leave this open-ended since the desired performance and cost limitations regarding coil-overs can be highly variable between customers.
Physical Prototype and CAD

Measurements were taken from the Volkswagen Bug to determine reasonable lengths for the A-arms, width of the subframe, and front track width. One half of the front suspension at full scale was then constructed from plywood and reasonably sized heim joints, shown in Figure 5, to check binding within the system, external factors absent. The model isn’t very refined but proves the basics of our idea within our budget and time limitations.

With similar dimensions and in parallel with the physical prototype development, we built up a CAD model that achieves an appearance much more like our intended final design. The model, shown in Figure 6, incorporates all the components that are in our design scope, as well as coil-overs for further constraining the model. The upright geometry is yet to be fleshed out, and though steering, brakes, wheels, hubs, and the vehicle roll cage are outside the design scope, they will eventually need to be integrated in the CAD to verify compatibility with all subsystems.
3.2 Manufacturing
During our ideation phases and concept designs we made sure to keep in mind manufacturability for our final design. For the boxed lower arms, mounting tabs, uprights and other parts that will be made out of sheet metal. This will most likely be made out of 1/8 inch 1008 Cold Rolled Carbon Steel. The thickness of this material may vary depending on the outputs of our FEA. In a production scale the parts that will be cut out of the plate will be made with a CNC Laser Cutter. What we will be using to simulate this is our CNC Waterjet here at Cal Poly. For all the tubular parts they would be made out of 1.5 to 1.75 inch diameter DOM. The wall thickness and diameter will be determined by the outputs of our FEA but based on our research we are looking at 1.5 in DOM .120 in wall. These initial values for wall thickness and overall size come from looking at what is popular within the off-road community and by talking to our sponsor. For large scale manufacturing this would be produced on a CNC Tube bender with a Laser notcher. For us, we have a pneumatic tube bender so that is what we will be limited to. We will be doing all of our tube notching with an abrasive belt tube notcher. We expect this kit to be welded with either MIG or TIG. There should not be a difference in performance between the two welding processes for what we are using them for. It is just personal preference of the welder or what the customer has in their shop.

4 Concept Evaluation
This section establishes confidence that the selected design will likely succeed in meeting the customer needs and wants. This confidence is established by comparing to similar designs, providing prototype and CAD measurements that prove our performance metrics are attainable, as well as laying out a plan for future verification. Additionally, discussion is included that shows we are aware of potential risks throughout the project, and that we have a plan of attack for addressing them.
4.1 Initial Verification

Much of our confidence that our design will work comes from precedent as well as recommendations we gathered during our research phase from experienced off-road builders and racers. The double A-arm independent front suspension concept is tried and true; our contribution to this field will primarily be making the parts and engineering them in a way that is accessible to DIY learners. For confidence that our design will perform competitively, we have compared our concept to the successful Nichols Fab front suspension kit [4], which uses the same construction as ours. In Appendix B – Pugh Matrices, it is seen that we expect our concept to have an above-datum ability to meet our customer requirements.

The prototype and CAD models provide measurable data as to whether our design can meet the intended engineering specifications. In Table 1, we can see the prototype and model at its maximums though its travel. Here, we see that our prototype can achieve 35 inches of vertical travel, though we do not have our steering rack yet integrated, which will significantly limit our vertical travel. With our CAD model we saw 17 inches of vertical travel, which just meets our requirements. We also analyzed our camber throughout the suspension travel, which can be seen in Table 2.

By assuming that the arms would statically sit about 15 degrees from the ground, we noted that we had 13 degrees of negative camber at static ride height. In our prototype, we measured 9 degrees of negative camber at full droop and 12 degrees of negative camber at full bump. These numbers are larger than we would like to see, but the 3 degrees of camber change is desirable, and the static camber can be offset by the upright pick-up points for about 2 degrees of negative camber at ride height.

Table 1 – Visual Comparison of CAD Model and Our Physical Prototype

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<td><strong>Full Droop</strong></td>
<td><img src="image3.png" alt="CAD Model" /></td>
<td><img src="image4.png" alt="Physical Prototype" /></td>
</tr>
</tbody>
</table>
Further design verification will be derived by comparing hand calculations to finite element analysis (FEA) results, and by consulting our sponsor for feedback as to whether our material thickness seems reasonable, based on his experience with existing designs. A second 3D printed mini-scale prototype will be constructed before the next design review to further verify the geometric capabilities of our design.

### 4.2 Potential Hazards and Prevention

There is an inherent possibility of danger with a vehicle suspension; the design will be heavy for lifting, most likely have pinch points, and may involve heavy masses above the user during assembly. The product is also intended for use in off-road racing, which requires user skill and can be dangerous in an accident or rollover. In the absence of full control over the product safety, we will minimize the hazards in our control by eliminating sharp edges in manufacturing, clearly marking pinch points, and providing clearance in the design where possible. All team members will discuss best practices and potential risks before any work is done in the machine shops or with the physical system.

It is important to note is that this design is meant to be for home-mechanics and enthusiasts, so while we will minimize safety concerns on our end, we ultimately cannot control the user’s safety practices while fabricated, integrating, and using the product. We can, however, prevent ignorant unsafe user mistakes by including relevant warnings in our fabrication and assembly documentation, providing welding tabs and fixturing to assist safe holding of parts during welding and assembly, and informing the user of the designed structural limits. Structural limits can be communicated with the technical values we will develop such as max load or energy input from the road to the suspension but will be most helpful to the user when communicated as a recommended top speed on example terrain. In the absence of destructive testing capabilities, we can include images of passing and failing welds, as well as direct users to visual weld inspection guides, such as the Fabricators’ and Erectors’ Guide to Welded Steel Construction [5], and include a disclaimer that the design will only function as intended for welds that meet the quality requirements. To somewhat ease this problem, we can assume weld strength corresponding to a low-intermediate skill level in our calculations and apply safety factors generously. A complete design hazards checklist is included in Appendix D – Design Hazards Checklist.

### 4.3 Challenges and Unknowns

Though we have researched and interviewed typical convention for A-Arm structural sizing, the expected loads and fatigue behavior of our designed parts, over years of high-intensity use, are still the largest challenge and unknown in our system. It is hard to accurately know the forces that will be acting on the design and some simplifications will need to be used.

Another current unknown is how different subsystems such as steering and braking will tie into our system. Although we have vague ideas on things like minimizing bump steer, and the range of motion of our heims, it is hard to predict the clearance we will have and the binding that will occur in our system.
Even though our prototype gave us 35 in. of vertical travel, that will be limited at a certain point by the steering system, coil-overs and other issues with clearance.

5  Project Management
In this section, we outline our project’s progress through the year, updated from the Scope of Work document. Key tasks, next steps, and a purchasing plan are discussed here to keep the team on track.

5.1  Timeline Update
Referencing Table 3, the Scope of Work project proposal document has been successfully submitted and accepted by the sponsor, and this report, along with its corresponding Preliminary Design Review (PDR) presentation will mark the completion of the second major project milestone. With the problem fully defined and design direction selected, the project now enters a modeling and analysis phase.

With the preliminary design done, the next step in the design process is to create more detailed part designs. This will continue naturally from the PDR concept CAD, integrating measurements from the Volkswagen Bug, as well as 3D models of purchased parts and systems. For each structural component of an assumed geometric form, material thicknesses will be sized by rough hand calculation, CAD geometry will be updated, and the projected structurally accurate geometry will be subject to the relevant worst-case load in Finite Element Analysis (FEA) for verification. Once all components pass, manufacturing drawings can be constructed from the CAD part files. A more detailed timeline up to the Critical Design Review is provided as a Gantt chart in Appendix E – Gantt Chart.

Table 3 – Key Milestones and Deliverables

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/16</td>
<td>Preliminary Design Review</td>
<td>Decision Matrix, Concept CAD, Basic Prototype</td>
</tr>
<tr>
<td>01/13</td>
<td>Interim Design Review</td>
<td>Detailed CAD Progress, Refined System Models</td>
</tr>
<tr>
<td>02/03</td>
<td>Review of Manufacturing Plan</td>
<td>Detail Drawings, Manufacturing Procedure Documentation</td>
</tr>
<tr>
<td>02/08</td>
<td>Critical Design Review</td>
<td>Detailed Analysis, BOM, Test Plans</td>
</tr>
<tr>
<td>02/17</td>
<td>Safety Review</td>
<td>Risk Assessment, Updated Test Plans</td>
</tr>
<tr>
<td>03/10</td>
<td>Review of Manufacturing and Test</td>
<td>Progress Documentation</td>
</tr>
<tr>
<td>04/26</td>
<td>Sign-Off on Verified Prototype</td>
<td>Finished Prototype Build</td>
</tr>
<tr>
<td>05/17</td>
<td>Design Verification Plan &amp; Report</td>
<td>Testing Plans for Evaluating all Engineering Specifications</td>
</tr>
<tr>
<td>05/24</td>
<td>Complete FDR Report</td>
<td>Written Report Containing Final Results</td>
</tr>
<tr>
<td>05/27</td>
<td>Senior Project Exposition</td>
<td>Final Prototype, Technical Poster</td>
</tr>
</tbody>
</table>

5.2  Purchasing Plan
Table 4 lists the materials and the purchased parts necessary for the kit completion. Other items, such as the coil-overs, steering rack, bump stops, and limiting straps, though necessary for functionality in the vehicle, are not included since they can be selected according to the customers’ preferences and are outside the kit cost for the customer. For this project most of the cost comes from buying raw materials such as the steel plates and the DOM (Drawn Over Mandrel) tubing. For most of our purchased parts, we are reaching out to companies through our sponsor’s connections for discounts and donations, but
have estimated the costs without these benefits in case. All purchased parts will be selected by the end of fall quarter and will be purchased for delivery two weeks before our manufacturing season begins.

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Estimated Price</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8 in 1008 Cold Roll Plate</td>
<td>$600</td>
<td>4ft x 8ft</td>
</tr>
<tr>
<td>1.5 in 0.120 in DOM</td>
<td>$200</td>
<td>20 ft</td>
</tr>
<tr>
<td>Steering Rack</td>
<td>$125</td>
<td>1</td>
</tr>
<tr>
<td>Joints and Bushings</td>
<td>$300</td>
<td>~</td>
</tr>
<tr>
<td>Hubs</td>
<td>$80</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Price</strong></td>
<td><strong>$1,385</strong></td>
<td></td>
</tr>
</tbody>
</table>

It may be noted that this cost build-up is for the project’s proof of concept that will be manufactured for this senior project, being less cost-effective than manufacturing multiple at a time. With our sponsor’s guidance, we will later estimate a direct sell-to-customer price based on 40 percent margin and outsourced manufacturing.

6 Conclusion

Our project goal was to design a long travel front suspension system for a VW Bug that could be manufactured as a DIY kit for Baja racing enthusiasts. This kit was intended to be as user friendly and affordable as possible. Since defining the scope of our project and writing our Scope of Work document, we refined our idea and came up with a solid general layout for the system. We performed concept definition, design, and justification, in order to narrow down our ideas to the best ones. This process began with performing ideation about our topic. Then we separated these ideas into four categories: arm layout, arm form, subframe, and upright. Within these categories, we refined our ideas using Pugh and Decision matrices, until we were able to decide on specific designs. Once we had a design direction, we built a concept prototype. This prototype helped us with our concept justification, allowing us to take geometry and vertical travel measurements, as well as giving us an idea of where and when binding might occur. Though these datums were important, we must now implement some of the complimentary subsystems, such as the coil-overs and steering system, to confirm these values.

We now request our mentor, Dave Schlossberg, to accept the selected design and/or provide corrective suggestions. Once the design direction is confirmed, the team will move on to our next phase of development, which will encompass selection of crucial subsystems such as the steering and brakes, as well as general structural analysis of our arms, subframe, and upright, based on industry-practiced worst-case load scenarios.
References


Appendix A – Documentation of Ideation Sessions

List of Ideas Considered

- Material / Manufacturing
  - Steel
    - 4130: TIG only limitation, costly, high specific strength
    - 1020/1026: MIG or TIG welding possible, cheaper, supply is more available
  - Aluminum
    - 6061: weldable, overall lighter, can be used on the skid plate but is softer than steel for dents and scratches
  - Other Material
    - Wood or composites: they are sometimes used for their structural compliance (for low load suspension, like RC aircraft landing gear)
    - Cardboard or PVC: could be used as a very cheap material for prototyping to-scale
  - Manufacturing methods
    - Tube (ex. DOM) vs plate
    - Little/no tooling: Water-jet, laser-cutter, 3D printing, welding
    - More tooling: Machining, casting, stamping
  - See if we can decide material and thickness by common standards

- Items that could be purchased
  - A whole “take-off” OEM system, where our project is just designing/fxturing the mount to the roll cage
  - Coilovers, bumps, straps
  - Rack and pinion steering system
  - Bushings, bearings
  - Stub axle and hubs
  - Brakes
  - Upright
  - Bolts / miscellaneous hardware

- Geometry / Configuration
  - Double A-arms
    - Tube vs plate
    - Parallel or not
    - Mount points not necessarily vertical to each other
  - Torsional trailing arm
  - Macpherson strut
  - Modular attachments to roll cage
  - Leaf spring
  - Streamlining or generatively designing components
    - Requires 3D metal printing
  - Pneumatic or mag-lev shocks vs coil-over
  - Silly ideas
    - Articulated limbs (octopus or caterpillar movement)
- Tank drive
  - Wings or hovercraft air-skirt suspension
  - Customer-facing assembly documentation
    - Youtube videos
    - Step-by-step written manual / internet blog
- Testing plans
  - Step function response in Simulink
  - Alignment curves
    - Cardboard & pins demonstration, dowel in tubes to mock shocks
    - Read from CAD software
    - Use a dial indicator for precise measurement on prototypes and final
  - Obtain dynamic suspension software
  - Drop or jump test the final vehicle
    - Accelerometer data (in cabin, on wheels)
    - Or simulate dynamics / FEA
Appendix B – Pugh Matrices

Arm Layout

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Double A-Arm</th>
<th>1) Equal Length Arms (Non-Parallel)</th>
<th>2) Equal Length Arms (parallel)</th>
<th>3) Shorter Upper Arm (parallel)</th>
<th>4) Shorter Upper Arm (Non-Parallel)</th>
<th>5) MacPherson Strut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Travel</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Min Bump Steer</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Durable</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cost</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Maintainable</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>+</td>
</tr>
<tr>
<td>Ease of Assembly</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>+</td>
</tr>
<tr>
<td>Build Quality</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Geometry Curves</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Customer DIY Involvement</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>S</td>
</tr>
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<td>“Total”</td>
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<td>-1</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
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</tbody>
</table>

Arm Construction

Subframe Layout
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Nichols Kit</th>
<th>Toyota 4-runner</th>
<th>C4 Corvette - aftermarket</th>
<th>Kartek Custom</th>
<th>Custom - Fabricated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>S</td>
<td>-</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Performance</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Maintainable</td>
<td>S</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Adjustable</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Quality</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Parts Available</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
<td>+2</td>
</tr>
</tbody>
</table>
Appendix C – Decision Matrices

### Arm Layout

<table>
<thead>
<tr>
<th>Criteria \ Concept</th>
<th>Importance</th>
<th>Equal Length Arms (Non-Parallel)</th>
<th>Equal Length Arms (parallel)</th>
<th>Shorter Upper Arm (parallel)</th>
<th>Shorter Upper Arm (Non-Parallel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Travel</td>
<td>38%</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Avoid Binding</td>
<td>33%</td>
<td>6</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Desirable Camber Curves</td>
<td>29%</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100%</strong></td>
<td><strong>6.33</strong></td>
<td><strong>8.54</strong></td>
<td><strong>8.63</strong></td>
<td><strong>7.67</strong></td>
</tr>
</tbody>
</table>

### Arm Form & Manufacturing

<table>
<thead>
<tr>
<th>Criteria \ Concept</th>
<th>Importance</th>
<th>Full Boxed Arm Design</th>
<th>Tubular Arm Design</th>
<th>Boxed Lower Arm &amp; Tubular Upper</th>
<th>Mixture of Boxed and Tubed Arms</th>
<th>Mixed Upper and Boxed Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer Interest</td>
<td>29%</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Cost</td>
<td>23%</td>
<td>3</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Durability</td>
<td>32%</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Weight</td>
<td>16%</td>
<td>3</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100.00%</strong></td>
<td><strong>6.42</strong></td>
<td><strong>7.39</strong></td>
<td><strong>7.61</strong></td>
<td><strong>7.35</strong></td>
<td><strong>8.19</strong></td>
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</tbody>
</table>

### Subframe Layout

<table>
<thead>
<tr>
<th>Criteria \ Concept</th>
<th>Importance</th>
<th>Rectangular Tube Box</th>
<th>Trapezoidal Tube Box</th>
<th>Curved Tube with Skid Plate</th>
<th>'T' Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>27%</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Weight</td>
<td>19%</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Clearance of Steering System</td>
<td>31%</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Customer Interest</td>
<td>23%</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100%</strong></td>
<td><strong>6.7</strong></td>
<td><strong>6.6</strong></td>
<td><strong>8.4</strong></td>
<td><strong>7.2</strong></td>
</tr>
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</table>
# Upright Geometry

<table>
<thead>
<tr>
<th>Criteria \ Concept</th>
<th>Importance</th>
<th>Toyota 4-Runner</th>
<th>C4 Corvette (aftermarket)</th>
<th>Kartek Custom</th>
<th>Custom Fabricated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>19%</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Maintainability</td>
<td>16%</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Durability</td>
<td>27%</td>
<td>3</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Adjustability</td>
<td>22%</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Part Availability</td>
<td>16%</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>2.43</td>
<td>2.43</td>
<td>4.81</td>
<td>5.51</td>
</tr>
</tbody>
</table>
### Appendix D – Design Hazards Checklist

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>×</td>
<td>1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?</td>
</tr>
<tr>
<td>×</td>
<td>2. Can any part of the design undergo high accelerations/decelerations?</td>
</tr>
<tr>
<td>×</td>
<td>3. Will the system have any large moving masses or large forces?</td>
</tr>
<tr>
<td>×</td>
<td>4. Will the system produce a projectile?</td>
</tr>
<tr>
<td>×</td>
<td>5. Would it be possible for the system to fall under gravity creating injury?</td>
</tr>
<tr>
<td>×</td>
<td>6. Will a user be exposed to overhanging weights as part of the design?</td>
</tr>
<tr>
<td>×</td>
<td>7. Will the system have any sharp edges?</td>
</tr>
<tr>
<td>×</td>
<td>8. Will any part of the electrical systems not be grounded?</td>
</tr>
<tr>
<td>×</td>
<td>9. Will there be any large batteries or electrical voltage in the system above 40 V?</td>
</tr>
<tr>
<td>×</td>
<td>10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
</tr>
<tr>
<td>×</td>
<td>11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
</tr>
<tr>
<td>×</td>
<td>12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?</td>
</tr>
<tr>
<td>×</td>
<td>13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?</td>
</tr>
<tr>
<td>×</td>
<td>14. Can the system generate high levels of noise?</td>
</tr>
<tr>
<td>×</td>
<td>15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?</td>
</tr>
<tr>
<td>×</td>
<td>16. Is it possible for the system to be used in an unsafe manner?</td>
</tr>
<tr>
<td>×</td>
<td>17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
</tr>
<tr>
<td>Description of Hazard</td>
<td>Planned Corrective Action</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Pinch points through suspension travel</td>
<td>We will make sure the be hyperaware and notify people working on the car when we are cycling the suspension.</td>
</tr>
<tr>
<td>Large moving masses/Car falling on someone working under it</td>
<td>Don’t work underneath hydraulics jacks only jack stands. Test the car to make sure its stable before you start working.</td>
</tr>
<tr>
<td>Pressurized Fluids</td>
<td>No welding on shocks containing pressurized gas. Safety Glasses will be worn. Brake lines will also be treated as pressurized lines and treated with care.</td>
</tr>
<tr>
<td>Possible for unsafe use</td>
<td>All precautions are discussed in the text, but it is ultimately up to the user to safely fabricate the suspension and operate their vehicle.</td>
</tr>
</tbody>
</table>
Appendix E – Gantt Chart
Part III: Critical Design Report

For
Dave Schlossberg at Poly Performance

Presented By
James Ankers jankers@calpoly.edu
Rebecca Hansen rhanse02@calpoly.edu
Dakota Hollingsworth dahollin@calpoly.edu
Thomas Spycher tspycher@calpoly.edu

Revised On
03/11/2022
Abstract

This report provides a progress update and design direction for the senior project of four mechanical engineering undergraduate students at California Polytechnic State University, San Luis Obispo. The document follows an earlier deliverable, the Scope of Work document (SOW), that defined the project goal to be to design a long-travel independent front suspension system for Baja off-road racing enthusiasts to weld together and integrate on a Volkswagen Bug at a low cost. Since then, we have performed concept development and submitted a preliminary design report (PDR). Using the feedback from our PDR we have altered our design in various ways listed in this report. We have edited our CAD (Three-Dimensional Computer Aided Design), to reflect these changes and provided detailed descriptions and drawings of all parts we will be fabricating. The report then discusses the justification of this design and details our FEA (Finite Element Analysis) results on the components of this system. Once this is complete, our manufacturing plan is discussed. This includes all the component specifications and drawings for the sub-assemblies, as well as details where all the necessary components and hardware will be obtained. Finally, we discuss our design verification plan and which tests will be performed in order to ensure the success of our design. These include testing various dimensions such as track width and vertical travel, as well as performing a laser test to measure bump steer.
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1 Introduction

We begin by reminding the reader of the project goal: to provide a way for Baja Racing enthusiasts to cost-effectively enter the sport with significant suspension performance gains (over a stock set-up) in off-road races, while gaining hands-on experience and cutting costs by assembling and partially fabricating their own independent front suspension system on the iconic Volkswagen Bug. It is intended that the system obtain at least 17 inches of vertical travel, maintain desirable tire angles and alignment curves for performance, avoid mechanical failure in a 20-mph arm impact or 3g landing on one front wheel, and cost under $1500 for the DIY kit consisting of critical geometry, mounting, and joints, without coil-overs.

The recent Preliminary Design Review (PDR) deliverable was accepted by the project advisor, Professor Sarah Harding, and sponsor, Dave Schlossberg, after recommending a shift away from our subframe with many bent tubes due to manufacturing tolerance and time considerations, which has led us to our final design to be described here. Dave also suggested considering smaller shocks with a 10 in stroke, but our customer was more interested in the performance of the larger shock. After considering all our shock options, we decided to design for the 12x2.5 King coil-overs.

Since the Preliminary Design Review, we have developed our CAD from conceptual to detailed, and have selected all the hardware for purchase and assembly. All these decisions can be seen in our iBOM (Indented Bill of Materials) and our drawing package in Appendix A and Appendix B.

This document describes our detailed system design, justification, manufacturing, and verifications plans. By the end of this document, the reader should have sufficient information to be able to fully build our prototype themselves and be convinced that our design will meet all engineering specifications and be safe in operation. The project sponsor will be asked to review and accept our design so we can begin manufacturing of the final prototype.

2 System Design

While our system design and functionality have not changed since our selected concept as presented in the PDR, we remind the reader that our overall system design is an independent front suspension, modeled with the typical double-wishbone configuration, typically seen in off-road vehicles obtaining high amounts of vertical travel. The vertical travel is achieved with the length of the upper and lower arms that amplify the linear travel of the spring and damper coil-over shocks with their sweeping motion. The upright provides mounting for the steering tie rods, wheel hubs, and brakes to make the vehicle functional. All components carry load up from the wheels and to the subframe, which ties into the vehicle’s structural roll cage, where loads can be resolved with inertial reactions.

The overall system design is represented in the labeled “exploded view” CAD of Figure 1, with detailed design descriptions of each subsystem to follow.
2.1 Subsystems
For a more detailed look into the design reasoning, we consider each subsystem separately.

2.1.1 Upper and Lower Arms
For our upper arm design, depicted in Figure 2a, we decided use steel tube with webbing plate. This design reduces weight compared to a fully boxed arm design made from sheet metal. Because the upper arm takes less stress than the lower arm, particularly bending stress, this construction is more desirable. Additional features seen are the brackets at the tip of the arm that provide the rotational joint connection with the upright, and the welded bungs set inside the tube for screwing in the heim joints that connect the arms to the subframe. These features are nearly identical on the lower arm.

For our lower arm, depicted in Figure 2b, we decided on a fully boxed construction. This arm is attached to the shock and will need to withstand large forces, therefore, having the extra strength and stiffness in that area is necessary, even if the design is heavier. An additional feature are the brackets set on top of the upper plate surface for mounting the shocks. Originally it was intended that the pivoting joint be located at the midplane of the lower arm thickness, but it was moved to avoid the problem of bolting on the angled side walls. This change is also preferable for adjustability and maintenance for the bolts or brackets.
Once we attach the arms to the subframe we will be welding our limiting strap tabs to the lower arms and the shock tower. We choose this route because it allows us to ensure that the limiting strap will not get entangled with any other components in our system throughout the arms travel.

Overall, our chosen arm geometry both benefit our packaging, the stiffness of the arm and the easy of manufacturing for our customer. Our main packaging benefit is that the J shape in the upper arm clears our shock body, so we do not have to worry about the potential chance of interference. We have also made sure that we are using the ideal placement of our suspension mounting tabs to get the most use out of our chosen shocks stroke length.

![Upper Arm CAD](image1.png) ![Lower Arm CAD](image2.png)

**Figure 2 - Arm CAD**

2.1.2 Subframe

After performing multiple iterations of the subframe design, our final concept incorporated a mix of both steel tubing and welded plate, shown in Figure 3. The boxed tube sections in the center of our subframe allow for flat locating of the tolerance-sensitive pick-up points for the arms, while the tube allows for larger, structural manufacturing using a tube bender. Although this might not be the best design for high production manufacturing, for our manufacturing capabilities, this would best allow us to complete the design successfully and efficiently within our time constraints. The side plates are added both for structure and to aid in the manufacturing and assembly tolerances by welding on the arm brackets first and then sliding the gussets side plate over the tabs thus locating our second datum, further discussed in the upcoming section 3.3.

Additional structure of note includes our bull bar, an outward protrusion from the subframe that acts as a deformable member in the case of a head-on collision, and routes loads into the core subframe geometry rather than through the shock tower, since the expensive shocks mounted at its tips could be damaged if the shock tower were to twist or otherwise deform.
2.1.3 Upright

After considering different uprights for purchase, we decided to custom fabricate our own upright. This allows us to be unconstrained by upright geometry and makes for a much cheaper design. These uprights feature a 1/8 inch steel 1020 steel plate box section, attached to our bearing housing tabs on either side. We will also have retaining straps that surround the tabs for added strength to prevent any possible chance of tear out. Figure 4 shows the manufacturing break-down of each part to be welded in the upright. We are waiting for the bolt on hubs we have selected to arrive. Once they do, we will be making some slight design changes to the front of the upright to accommodate its bolt pattern as well as weld nuts and internal support. For our bearing housing they will have to be waterjet then post machined. Our post machining will include boring out the hole to the manufactures press fit recommendation, adding a slight lip for our selected COM bearing to sit against and machining a snap ring groove to fully secure the COM bearing which is talked about more in the Hardware Section.
2.1.4 Hardware
Our design incorporates various purchased parts, such as joints and shocks, that connect our manufactured parts together.

2.1.4.1 Coil-overs
For this design, we decided to purchase 12x2.5 coil-overs, where 12 indicates the stroke length in inches, and 2.5 indicates the shock diameter, also in inches. The 12-inch stroke length enables our vertical travel goals, while the large shock diameter and corresponding fluid volume prevents fading, where the shock fluid heats up during a race and loses viscosity and effectiveness and damping vibration. The design likely could have functioned with shocks as small as a 10x2.0, but our customer was more interested in the performance of the selected shocks over the cost savings from sizing down.

2.1.4.2 Limiting Straps
To spread out the impulse when the suspension reaches its full droop position, we will be incorporating limiting straps into our design. These straps help preserve the shock from being destroyed. We will be using a 15 to 16 inch limiting strap to ensure that we can contain the suspension travel within the limits of the shock. These straps have about an additional inch of stretch while loaded [1].

2.1.4.3 Bump Stops
To limit the travel at max compression, we plan on using simple polyurethane bump stops purchased from Poly Performance [2]. These bump stops are the simplest, and cheapest option, but because of how light a Volkswagen Beetle is they will work. The other options would be to use air or hydraulic bumps. These perform better but cost more than double the price. Therefore, to reduce complexity and
cost of our design we will be using simple polyurethane bumps. We plan on attaching the bump stops to the top of the upper arms. However, the exact placement of the bump stop has not been decided, as it will depend on the geometry of the roll cage.

2.1.4.4 Hiem and COM Joints
For our main joint connections, we will be using FK rod ends and COM joints. These joints from FK feature corrosion resistant material properties as well as tight tolerancing to not allow foreign degree from damaging the bearing surfaces. For the uprights we have chosen COM14 sized bearings which have a rated radial load of 41,960 lbf. The Rod ends that we have specified JMX12 which have a rated axial load of 28,090 lbf. With the front end of our car being light compared to other off-road race vehicles, the hardware in this design is slightly over-built for some of our load cases but with this we are able to increase our factor of safety significantly.

2.2 Cost Breakdown
Our upcoming build, known in the senior design course as the Verification Prototype, is intended to be the final build that gets fully integrated onto the vehicle, so all materials and hardware purchased will be to actual specification, with little margin for error in our budget. Recalling our Scope of Work document, our goal was to have a competitive at-home build kit cost under $1500. This includes all the geometry and assembly hardware, without mating components and assemblies necessary for the vehicle to function, as similar kits are sold. This leaves our in-scope cost estimate, shown in Table 1, to only include the raw materials to fabricate custom arms, subframe, and upright, as well as the heim joints and bearings included in the assembly stage. It may be noted that effort was made to use the same material stock in as many custom components as possible, to decrease material waste and purchasing and shipping costs. The full project budget, including out-of-scope components that we have purchased or plan to purchase can be found in Appendix C.

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<th>Components In Scope</th>
<th>Cost</th>
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<tr>
<td>1.5 OD x .120 wall 1020 Mild Steel DOM (20ft)</td>
<td>$ 230</td>
</tr>
<tr>
<td>1/8 in. 1020 Mild Steel Cold Rolled Plate (4ft x 8 ft)</td>
<td>$ 450</td>
</tr>
<tr>
<td>1/4 in. 1020 Mild Steel Cold Rolled Plate (1 ft x 2 ft)</td>
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</tr>
<tr>
<td>6 in x 3 in x .120 wall Box Tube (4ft)</td>
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</tr>
<tr>
<td>Hardware</td>
<td>$ 750</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$ 1620</strong></td>
</tr>
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</table>

3 Design Justification
Once we determined realistic load cases that our design would see, we then had to choose proper material thicknesses for our design to successfully perform as expected. We created our base line of material thickness by looking at what other competitors used in their products and went from there. We
made adjustments in places that showed high stresses and places that could improve on the industry standard.

We plan on using 1.5” OD x .120” wall 1020 mild steel for our design. With this material we can obtain a safety factor of at least 2 at all points in our design. It is also important to mention however, that our sponsor has scrap 1.5” OD .188” wall 4130 tubing that we might be able to use. This would be over engineered but would save us a substantial amount of money.

3.1 Engineering Specifications in CAD
We remind the reader that some of our primary engineering specifications are based off the dimensions of our final assembly, particularly the 72 inch limit on the track width of the vehicle for legal road-driving, and the 17 inches of vertical travel goal for avoiding obstacles and dissipating impacts in a high performance off-road setting, and maintaining camber between 0 and negative 5 degrees for cornering. We are confident in our ability to meet these specifications based on the successful CAD model presented in Figure 5.

![Figure 5 – Design Measurements](image)

3.2 Analysis Conducted
Our primary topic of analysis is structural failure in any of the many parts in our system. However, a barrier to our analysis is that the way loads flow through all the components is not at all immediately intuitive, and it reasonable requires a full-system finite element analysis (FEA) to simulate the resultant loads in each component from our design load cases. Since we have been developing and redesigning our CAD multiple times over in parallel with the scheduled design justification deliverables, we have not yet had the ability to perform this more in-depth analysis. Though we still plan to conduct the full system FEA later as part of our verification process, in the meantime we have conducted rough hand calculations and some individual component FEA’s to prove our design concept is on the order-of-magnitude correct.
For our first round of FEA based failure analysis, we will simulate a few ‘worst-case scenario’ load cases, such as a 3g vertical landing on one wheel and a 20-mph front collision. As these initial load and stress analysis studies are intended to provide a broad insight to the potential failure points of our system and will feature a relatively low fidelity model of the load paths in our system, we will simulate each component individually, as opposed to a complete system. The components we will be analyzing will be the upper & lower control arms and the upright, as these components are expected to bear the highest levels of stress during operation. The results were that every part analyzed had a much larger safety factor than the minimum 2.0 goal, and that much of the material is much safer than that. We were able to use the FEA to identify a design change to eliminate a high stress location by extending the webbing plate on the upper arm to the very edge of the root. Further discussion on the preliminary FEA can be found in Appendix D.

Much of our geometry does not lend itself to simple calculation, but the hardware can be reasonably sized with hand calculations. Considering the double-shear joints where the arms connect to the upright, our most important properties were the 42,000 lb swivel joint static radial rating, 140 ksi shoulder bolt tensile strength, and 50.8 ksi plate steel yield strength. Without knowing the load sharing through the different components, our 3g (or 6000 lb) vertical landing can be conservatively assumed to flow entirely through one arm. From the calculations included as Appendix E, we predict a worst-case safety factor of 1.9 for shear-out, 3.2 for bearing in the bracket, and 7.7 for shear through the bolt. While the shear-out case is technically under our 2.0 acceptable minimum, the load through just one arm assumption is extremely conservative, so we expect the detailed verification FEA to obtain a safety factor above 2.0 without a design change. We also see that the bolt is fairly oversized, but its diameter is set by the inner diameters of the desired swivel joint, bearings, and heims, so this result will also not drive a design change.

### 3.3 Design for Manufacturing and Assembly (DFMA)

An important part of our design justification is proving our ability to manufacture our final assembly with the precision needed to produce a high-quality product and meet our engineering specifications. This subsection discusses how our design was refined for manufacturability and our proof of concept that shows we can notch, cope, and weld tube.

#### 3.3.1 Arm Pick-Off Points Tolerance

The most tolerance-critical aspect of our design is making sure the arm pick-off points are precisely located relative to each other, so we have modified our subframe to accommodate milled slots in our box tube for locating and welding in our suspension arm brackets, with an added side plate that connects the upper and lower box tubes and has slots to slide over the welded suspension arm brackets. The side plates will be waterjet with 0.012 in tolerances and will serve multi-purposely as a jig that locates the arm brackets and box tubes relative to each other, prevents warping during welding, provides additional welding surface for the brackets, and provides a vertical load path from the arms and out through the subframe to the roll cage.

With the core of our geometry using flat faces for datums and continuous pieces for locating features, the rest of our subframe can extend out from the core with structural bent tube that doesn’t require tight position tolerance.
3.3.2 Structural Prototype

While the bulk of our parts will be very easy to cut two-dimensionally on the waterjet, and we have removed tight tolerance requirements on our bent tubes with our new subframe design, we expect the hardest manufacturing step in our project will be cleanly coping all our bent tubes together and being able to weld all around our joints. To prepare for this difficulty, we have manufactured a structure which can be seen in Figure 6 that incorporates the type of joints we will be seeing withing our tubular parts for practice before getting our hands on the final prototype, where we don’t have the budget for mistakes. In this we learned and practiced most of the manufacturing steps we will be using to create our final prototype. This welded structured involved us cutting, coping, mitering, weld prepping and welding tubes. Our final take from this prototype is the importance of welding preparation as well as being a skilled welder. We plan to take time in the shop in the coming weeks to increase our welding knowledge and skills. In Figure 7 we included closer pictures of some of our welds.

![Figure 6 - Structural Prototype Welding Structure](image-url)
3.4 Safety, Maintenance, and Repair

One of the main safety concerns we addressed in our design is prevention of dirt and water from getting into our tube structures that could cause hidden corrosion that breaks down our parts from the inside-out.

For maintaining our design, it is up to the user to visually inspect the suspension and structural integrity after every race to verify its condition. This is a common practice for any racer/race team under regular maintenance. This would include visual checks of welds for cracking or failure, deformation of members, and bolt checks. We also suggest that the Rod ends, and COM bearings be closely inspected after each race season. Depending on the wear, it should be replaced with new FK joints.

These Baja race cars take a beating and sometimes see a large load that can fall outside of our design criteria. We heavily emphasize the importance of the maintenance inspections because that is how you are going to find damage that can potentially turn into a catastrophic failure. If a weld cracks it can be repaired through the processes of chasing out the crack and reinforcing the damaged area. While working on the car we will be referring to our latest FMEA and Design Hazard Checklist can be found in Appendix F and Appendix G, as well as our risk assessment and mitigation techniques for the customer are seen in Appendix H.

4 Manufacturing Plan

Once our design had been selected, we laid out how we plan on building this design. This was split up into two sections, procurement, and manufacturing. A detailed timeline that includes our manufacturing steps can be found in our Gantt chart in Appendix I, and more on procurement, materials, and manufacturing can be found in our Component Specification table in Appendix J.

Since we have a lot of parts to manufacture, we must start early. We will be following the manufacturing plan laid out by our Gantt chart which can be seen in Appendix I. The first step will be purchasing all of
our raw materials. From there we will be looking at laying out the subframe. Secondly, we will be cutting out all the parts that need to be waterjet and then creating welding jigs for our arms and uprights.

4.1 Procurement
Most of our parts will be custom-made by us in the Cal Poly shops, excluding bearings and assembly hardware which will be purchased mainly from McMasterCarr.com and FK for their quality specifications and part CAD availability. We will also purchase suspension components such as shocks, bumps, and straps from Poly Performance. Once our part thicknesses are verified with structural calculation and FEA, material will be purchased from B&B Surplus in Santa Maria, with an approximate one-week lead time and free shipping for an order of our size. A full purchase list for in-scope parts is included in Appendix C.

In parallel, our customer has already purchased a steering rack and wheel hubs, and other mating assemblies outside the immediate project scope will be purchased in the coming weeks so that our final manufactured prototype may be assembled as realistically as possible.

4.2 Manufacturing & Assembly Steps
Our manufacturing steps are rather lengthy, so we have included them as Appendix K. In short, most of our components will be comprised of plate cut out on the waterjet and tube bent with a single die on the Tube Shark. Scrap-wood jigs will be used to assist in alignment and tacking before full weld processes, and surface preparation and finishing is described for the welding operations. Some additional features will require a boring operation for press-fitting hardware.

After the components are welded up, their assembly is rather simple. Heim joints are threaded into the bungs of the arm with Loctite and dialed in to the desired arm length, Delrin washers are placed on either sides of the heims to prevent marring, and the joint is completed with a shoulder bolt, nut, and washer. The joints are equivalent for the shocks and connecting the arms to the upright, though misalignment spacers replace Delrin washers to allow for the rotation needed in steering on the upright end. An exploded view of the assembly broken into components and assembly hardware is seen in Figure 8.

![Figure 8 - Exploded Assembly View](attachment:image)
5 Design Verification Plan (DVP)

Many of our tests will require measurements of the final build to properly verify our engineering specifications, so we additionally plan to use CAD, FEA, and relevant practice tests to check our design earlier in the process. A discussion of all our verification and testing plans is provided here, while our DVP table with further details is provided as Appendix L, and the timeline for each test can be seen in our Gantt chart in Appendix I.

Since we don’t have the budget for full component destructive stress tests, we’re planning a multi-body FEA of the whole system to see how the forces actually distribute through each component and will be accepting a minimum yield safety factor of 2. Additionally, we will complete some practice welds connecting plate to tube and tube to tube, and destructively test these coupons on one of the Instron tensile testing machines on campus. The ultimate weld tensile strength we obtain in these tests, adjusted with data analysis and uncertainty propagation, will be noted along with details from a visual inspection of the weld, so we can be better grounded as to our actual weld quality when we do the visual weld inspections on our final build.

The first tests performed will be to measure Track width and Bump Steer. Our goal is to obtain a track with of 72 +/- .5 in, and a vertical travel of at least 17 in. These will be easy to measure by simply using a tape measure. Through our CAD design we were able to obtain theoretical predictions for these values, as presented in 3.1 and due to our manufacturing processes, we are confident that we can successfully provide the desired tolerances on these values. However, in order to make sure, we will be required to take physical measurements of the completed design.

The next test, which is slightly more complicated, is to measure bump steer. This will be done by attaching a laser to the upright and cycling the suspension through its travel. If the laser is pointed at a wall, its movement can be graphed, with the vertical measurement being camber and the horizontal measurement being toe. For there to be no bump steer, the toe value must not change, so the laser must make a perfectly vertical line on the wall. The line on this graph will change depending on where the steering rack is located, so by doing this with different steering rack heights, the perfect height can be obtained.

6 Conclusion

We have now completed the design of a long travel front suspension system for a VW Bug. After multiple CAD iterations we have designed a system and specified the necessary components to complete this design. With all the preliminary design and analysis completed, our next step is manufacturing. This document provided a summary of our design, justification, cost estimate, manufacturing plan, and finally our design verification plan.

In summary, our double A-arm suspension design will be manufactured with a boxed lower arm, and tube upper arm with webbing. Our subframe will be manufactured out of a combination of boxed sheet metal and DOM tubing. The subframe will also include gusset plates on either side to serve as locating points for the arm pick-ups to help us achieve tight tolerances on our design.
This design will mostly be waterjet and welded. In addition, the tube bender will be used for the subframe and upper arms. In order to verify this can successfully be completed, we will perform a structural prototype in the form of manufacturing practice.

We anticipate this project to cost around $1500. This only including materials that are directly used in the design. For the vehicle to be functional, other components such as shocks, and a steering rack must be purchased as well.

Finally, once the design has been manufactured, various measurements will be taken to confirm that we have met our specifications. We will measure track width and vertical travel. We will also perform a laser test to measure bump steer and locate the best place to mount our steering rack. After presenting this information, we now ask our sponsor, Dave Schlossberg, to accept our design and/or provide any suggestions. Once our design has been accepted, we will continue purchasing the necessary materials and begin our manufacturing process.
References


## BAJA BUG INDEPENDENT FRONT SUSPENSION

**Indented Bill of Material (iBOM)**

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**Total Parts** | 161 | $ 2,097.92 |
Appendix B | Drawing Package

Table: Parts List

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<td>Crossover</td>
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Title: Baja Bug Front Suspension

Overall Assy - Exploded

Approved: [Signature]

Checked: B

Drawn: Thomas Spyker 3/25/2022

Scale: 1:10
Note: Sweep Profile will be further defined in Bend-Tech Software. The end bracket will also be further defined in a .dxf file for the water jet.
Baja Bug Front Suspension
LCA Dimension Drawing

2x 3/4 in. Hems

2.25
1.13
20.75
2.25
13
2.43
2.25
13
1.74
3.77
6.5
2.38
.35
14.04°
30
6
Concept CAD
Title: Straight Tube Dimensions

Dimensions:
- 19.33
- 45°
- 45°
- 13.57
- 9.98
- 17.02
King Shock Spec Sheet (Part Number 13000)

<table>
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<tr>
<th>Part#</th>
<th>Description</th>
<th>Type</th>
<th>Details</th>
<th>Weight</th>
<th>Compressed length</th>
<th>Extended length</th>
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<td>(w/o springs)</td>
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<td>24.000</td>
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Limiting Strap Spec Sheet (Part Number 13500)

Poly Performance Quad Wrapped Ultra Strength Limit Strap

- Plated end fittings are made from tough 4130 steel & have 1/2" hole
- U.S. made 1.75" nylon webbing with a 7000 lb. rating and superior flexibility
- Available in quad wrap (ultra strength)
- Eyelets have an integrated deflector clip to minimize abrasion
- Limit Strap length is measured from center of mounting hole to center of mounting hole
- Straps will stretch 1" for every 12" under load
- Limit Straps Priced Individually

From

$20.00

SKU#: PPI-LS_PARENT_ITEM

Military|Responder|Medical Discounts GET VERIFIED

Part #

Choose an Option...

1 Add to Cart

Likes |

Email |

Facebook | Twitter | Pinterest | Reddit
Note: Sheet metal dimensions are the same on the left side but bends are mirrored.
Notes: Type 303 Stainless Steel Housing
Heat-Treated, Type 440C Stainless Steel Ball
PTFE-Lined, Type 303 Stainless Steel Insert
### Appendix C | Project Budget

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<th>Out of Scope Components</th>
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<td>Bump Stops</td>
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<td>Limiting Straps</td>
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<table>
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<tr>
<th>Components In Scope</th>
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<td>¾ in. Mild Steel Cold Rolled Plate (1 ft x 2 ft)</td>
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<td>6 in x 3 in x .125 wall Box Tube</td>
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<td><strong>Total Cost</strong></td>
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Appendix D | Finite Element Analysis

The first simulation we will address is the 20-mph front collision, as this reflects the greatest reasonable load the system is expected to experience. This collision is an impact event occurring at the tire, and is modeled by a 2,500 lbf force applied at the joints between upper and lower control arm, and the upright. Our primary concern here is in-plane bending in the control arm, and shear stress experienced by the brackets which the upright is mounted to. Our overall results (Figures 8 – 10) were satisfactory; peak bending stress within the arms was 11.94 ksi in the upper arm, and 12.4 ksi in the lower arm.

Figure 9 – FEA results of bending stress in the upper control arm

These stress levels result in a factor of safety of 4.16 for our chosen material (1020 steel), which has a yield strength of 50.8 ksi. Shear stress within the mounting tabs which secure the upright had a peak
value of 20.58 ksi, which results in a factor of safety of 2.44. Results are similar for the mounting tabs on the lower arm (shown below), with peak Shear Stress values of 25.6 ksi, which results in a factor of safety of 1.98. While this is just under our desired value of 2.0, these peak stress levels occur near a stress concentration created by the change in thickness of the mounting bracket, which should be easily corrected by incorporating a slightly larger fillet in this area.

The second simulation was used to model our second worst-case loading scenario of a 3g vertical impact on one wheel, which simulates the vehicle landing from a jump at an angle on one wheel. This was modeled by a 2,500 lbf impact load at the upright-pickup bracket, which creates a resultant 2,500 lbf force created by the coilover resisting the upwards motion of the suspension arms. This load case results in some potentially high bending stresses, however these loads are easily handled by our chosen boxed-steel lower control arm design, with the maximum stress being around 12.4 ksi. This results in a factor of safety of 4.09, which is more than 2x our desired minimum value.
This second load case also represents the peak forces we expect our upright to encounter and was simply applied to our upright by a 2,500 lbf bearing load that results from the same load pathing that was modeled in Figure 10 (bending within the lower arm). Peak stress levels seen in the dog ears which will support our COM bearings are around 24-25ksi, which results in a minimum factor of safety of 2.04. While this meets our minimum requirements, we later went back and added some sheet metal straps that will secure these dog ears to the main body of our upright and eliminate any possibility of shear-tear out on these lug-style ears. Simulation on this strengthened design has not been conducted yet, as we are planning to revisit this on our second, more in depth pass of multi-body FEA.
Appendix E  | Hand Calculations

**Hand Calculations**

**Bolt**

- **Properties**
  - Bolt $S_y = 140 ksi$  
  - Plate $S_y = 50 ksi$  
  - $S_y = 25 ksi$  

**Tensile Force**

- $F = 3g$ through joint
- $F = 6000 lb$

**Stress Calculation**

- $S_b = \frac{F}{A}$
- $A = \frac{d^2}{4}$
- $d = .75$
- $w = 1.75$
- $K_t = 2.11$
- $K_{fs} = 2.11$

**Bolt Shear**

- $C_v = \frac{9V}{3A} = \frac{9(5000 lb)}{3(\frac{d^2}{4})} = 9054 \text{ lb}$
- $SF = \frac{20 ksi}{9.054 ksi} = 2.2$

**Plate Bearing**

- $F = \frac{1}{n} \left( \frac{2V}{d} \right)
- \text{SF} = \frac{25 ksi}{60 ksi} = 0.42$

**Discussion**

In this we have some configurations that are irregular geometry in the case where our design is more robust than what some of these hand calcs show, for example, since we need a small angular range of motion, we can add hood covers to the tops of our sus tabs as drawn to the right but these are hard to analyze due to the welds.
## Appendix F | FMEA

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<th>Potential Causes of the Failure Mode</th>
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<th>Occurrence</th>
<th>Current Detection Activities</th>
<th>Detection</th>
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<th>Detention</th>
<th>Previous Effort</th>
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<td>Weld Failure, Wear, Geometry, Material Choice, Material degradation from corrosion inside box or tube</td>
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<td>Verify load capacity with FEA</td>
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<td>Decreased cornering performance, excessive steering effort required</td>
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<td>3</td>
<td>Measure alignment on CAD, physically verify measurements on a 3D printed mini prototype</td>
<td>CDR</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>Transfer Load</td>
<td>Weld failure, material failure, bolt shear</td>
<td>Loss of all wheel control</td>
<td>9</td>
<td>Undersized weld design, low quality weld manufacturing, thin material, insufficient material around bolt holes</td>
<td>Design weld to be stronger than base material</td>
<td>5</td>
<td>FEA analysis, visual weld inspection</td>
<td>5</td>
<td>Conduct motion interference simulation in CAD, physically verify range of motion in a 3D printed mini prototype</td>
<td>CDR</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface with arms and tie-rod</td>
<td>Upright binds on arms</td>
<td>Not enough steering angle, undesirable bump steer feedback</td>
<td>Failure on arm joints, with adequate range of motion</td>
<td>3</td>
<td>Poor design layout, Excessive bearing wear, feedback</td>
<td>Select high joints with enough range of motion</td>
<td>3</td>
<td>Verify range of motion in CAD</td>
<td>2</td>
<td>Upright binds on arm, Select high joints with enough range of motion</td>
<td>CDR</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subframe</td>
<td>Transfer Loads</td>
<td>Mounting brackets break, subframe breaks off the roll cage</td>
<td>Diminished control of vehicle</td>
<td>9</td>
<td>Weak geometry, Design with strong geometry</td>
<td>Design for load capacity with FEA</td>
<td>3</td>
<td>Verify load capacity with FEA</td>
<td>3</td>
<td>Mounting brackets break, subframe breaks off the roll cage</td>
<td>CDR</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix G | Design Hazard Checklist

<table>
<thead>
<tr>
<th></th>
<th>Y</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>×</td>
<td>1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>2. Can any part of the design undergo high accelerations/decelerations?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>3. Will the system have any large moving masses or large forces?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>4. Will the system produce a projectile?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>5. Would it be possible for the system to fall under gravity creating injury?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>6. Will a user be exposed to overhanging weights as part of the design?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>7. Will the system have any sharp edges?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>8. Will any part of the electrical systems not be grounded?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>9. Will there be any large batteries or electrical voltage in the system above 40 V?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>14. Can the system generate high levels of noise?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>16. Is it possible for the system to be used in an unsafe manner?</td>
<td></td>
</tr>
<tr>
<td>×</td>
<td>17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinch points through suspension travel</td>
<td>We will make sure the be hyperaware and notify people working on the car when we are cycling the suspension.</td>
<td>4/5/22</td>
<td>TBD</td>
</tr>
<tr>
<td>Large moving masses/Car falling on someone working under it</td>
<td>Don’t work underneath hydraulics jacks only jack stands. Test the car to make sure its stable before you start working.</td>
<td>2/22/22</td>
<td>TBD</td>
</tr>
<tr>
<td>Pressurized Fluids</td>
<td>No welding on shocks containing pressurized gas. Safety Glasses will be worn. Brake lines will also be treated as pressurized lines and treated with care.</td>
<td>3/29/22</td>
<td>TBD</td>
</tr>
<tr>
<td>Possible for unsafe use</td>
<td>All precautions are discussed in the text, but it is ultimately up to the user to safely fabricate the suspension and operate their vehicle.</td>
<td>5/17/22</td>
<td>TBD</td>
</tr>
</tbody>
</table>
### Appendix H | Risk Assessment

**Designsafe Report**

- **Application:** Baja bug
- **Description:**
- **Product Identifier:** Detailed
- **Assessment Type:** Detailed
- **Limits:**
- **Sources:**
- **Risk Scoring System:** ANSI B11.0 (TR3) Two Factor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Methods / Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Status / Responsible / Comments / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-1</td>
<td>All Users Common Tasks</td>
<td>mechanical : crushing Negligence</td>
<td>Serious Remote</td>
<td>Low</td>
<td>instruction manuals</td>
<td>Serious</td>
<td></td>
<td>/Crushing is really only possible with improper use of jack stands</td>
</tr>
<tr>
<td>1-1-2</td>
<td>All Users Common Tasks</td>
<td>mechanical : cutting / severing Sharp Edges</td>
<td>Minor Likely</td>
<td>Low</td>
<td>warning label(S), gloves, Debur parts</td>
<td>Minor</td>
<td></td>
<td>/Wear gloves when handling parts near cut edges</td>
</tr>
<tr>
<td>1-1-3</td>
<td>All Users Common Tasks</td>
<td>mechanical : drawing-in / trapping / entanglement Negligence</td>
<td>Serious Remote</td>
<td>Low</td>
<td>warning label(s)</td>
<td>Serious</td>
<td></td>
<td>/This is very unlikely. A combustion of things must go wrong before this occurs;</td>
</tr>
<tr>
<td>1-1-4</td>
<td>All Users Common Tasks</td>
<td>mechanical : pinch point Improper use, negligence</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>warning label(s), gloves</td>
<td>Moderate</td>
<td></td>
<td>/There is a very low chance of pinching when working on the arms. More of a risk when setting down material</td>
</tr>
<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Risk Reduction Methods / Control System</td>
<td>Final Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Status / Responsible / Comments / Reference</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
<td>------------</td>
<td>----------------------------------------</td>
<td>--------------------------------------</td>
<td>------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>1-1-5</td>
<td>All Users Common Tasks</td>
<td>mechanical: head bump on overhead objects Negligence</td>
<td>Minor Likely</td>
<td>Low</td>
<td>instruction manuals</td>
<td>Minor</td>
<td></td>
<td>/This is if someone is working under the car. Bound to happen at least once.</td>
</tr>
<tr>
<td>1-1-6</td>
<td>All Users Common Tasks</td>
<td>Welding: uncontrolled ignition sources Improper Work Area Flammable Objects Near Welding Flammable Liquids Near Welding</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>special procedures, standard procedures, instruction manuals</td>
<td>Serious</td>
<td></td>
<td>/make sure gas, acetone, other serious flammables are away while welding</td>
</tr>
<tr>
<td>1-1-7</td>
<td>All Users Common Tasks</td>
<td>Welding: hot surfaces Welding</td>
<td>Moderate Likely</td>
<td>Medium</td>
<td>gloves, special clothing, footwear</td>
<td>Moderate</td>
<td></td>
<td>/Don’t touch hot stuff!</td>
</tr>
<tr>
<td>1-1-8</td>
<td>All Users Common Tasks</td>
<td>Welding: exposed electrical arcs During Welding Process</td>
<td>Minor Remote</td>
<td>Negligible</td>
<td>safety glasses, special clothing</td>
<td>Minor</td>
<td></td>
<td>/Wear your PPE and know who’s around you. Communicate before you start welding.</td>
</tr>
<tr>
<td>1-1-9</td>
<td>All Users Common Tasks</td>
<td>Welding: Inadequate Welds Total System Failure, Inexperienced</td>
<td>Catastrophic Likely</td>
<td>High</td>
<td>awareness barriers, warning sign(s), instruction manuals, video, on-the-job training (OJT), Hands on Experience</td>
<td>Catastrophic</td>
<td></td>
<td>/This is not a kit for a beginning welder. Make sure you get good welding experience before you attempt this project</td>
</tr>
<tr>
<td>1-1-10</td>
<td>All Users Common Tasks</td>
<td>heat / temperature: burns / scalds Touching Hot Welds</td>
<td>Serious Likely</td>
<td>High</td>
<td>standard procedures, safety glasses, footwear, special clothing, gloves</td>
<td>Serious</td>
<td></td>
<td>/Wear PPE. Don’t touch hot stuff!</td>
</tr>
</tbody>
</table>

H-2
In the risk assessment above there is a column that describes ways to mitigate the risks under Risk Reduction Methods. Below is a more detailed explanation of how to avoid or prepare for some of these risk and hazards. We wanted to first address the high-level risk then medium level risk.

**Risk Item # 1-1-9:** This kit could and will be dangerous for someone to use if they are not a confident welder. If this kit contains poor welding practices, then it is bound to fail within our range of loads. We recommend that you are comfortable on the welder and have some form of welding training.

**Risk Item # 1-1-10:** We want to make clear that it is important to be careful when welding. This involves letting parts cool properly, being mindful of where you touch your parts before and after a weld and as well as working around others. Serious burns can occur from touching hot metal. Please wear proper leather gloves for welding.
**Risk Item # 1-1-13:** While welding it is important to prepare your material before welding to curb any contamination and porosity from occurring. This involves cleaning your material with acetone. Since acetone is highly flammable and might be exposed to high temperatures while welding, it is good practice to store the acetone as well as the rags used to clean the material far away from the place of welding. There are numerous reported accidents from experienced welders in the school shops of rags accidentally catching on fire because they are within the vicinity of the welder.

**Risk Item # 1-1-6:** While welding there is a chance for something in your surrounding area to ignite. Make note of materials that are within this area that are flammable. We advise that there is a fire extinguisher within reach of the welding area. Some items may be unavoidable such as the wall. We suggest welding on a metal welding table. Please be aware of your surroundings while working.

**Risk Item # 1-1-7:** Because you are welding you will be exposed to hot surfaces. To mitigate any burning again be mindful of what you are welding and where you have previously welded. Wear proper PPE. This would include a welding helmet, a cotton long sleeve shirt, cotton work pants, close toed shoes. You should also not wear in any circumstance while welding synthetic clothing as it melts to the skin when it burns.

**Risk Item # 1-1-12:** While welding you want to be in a decently ventilated area. You also do not want to weld any stainless steel, galvanized steel or any painted or coated materials without proper ventilation systems and respirators. In this kit there will not be any of these include. You are working with other gases. You want enough air to have proper circulation of the room. This can be leaving the garage door open or having a box fan in the side of the shop. There is also a place for too much ventilation where your shielding gasses are being blown away and allowing for porosity into the weld and oxidation. Be mindful of this because this can lead to weld failure.

**Risk Item # 1-1-14:** While welding you are being exposed to harmful and intense UV rays. Make sure you are welding proper welding PPE. Your welding helmet should be set to around 10-12 for a shade setting. Do not look at someone welding without a helmet. This can cause a sunburn on your eyes. Also be mindful when welding around others so they have time to prepare when you weld. Again you should also be wearing long sleeve clothing and long pants to minimize exposed body parts to these UV rays.
# Appendix J  | Component Specifications

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Purchase (P)</th>
<th>Modify (M)</th>
<th>Build (B)</th>
<th>Raw Materials Needed to make/modify the part (only M &amp; B)</th>
<th>Where/how procured?</th>
<th>Equipment and Operations anticipate using to make the component</th>
<th>Key limitations of this operation places on any parts made from it</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Suspension</td>
<td>Subframe</td>
<td>B</td>
<td>1/4 Wall 3”x 6’ Box Tube</td>
<td>All Box Tube Purchased through McMastercarr</td>
<td>Mill to Slot Suspension Tabs Welder to Attach to Chassis</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Control Arms</td>
<td>B</td>
<td>1/8 in. 1008 Cold Roll Plate 4’ x 8’</td>
<td>All Plate Purchased through B&amp;B Surplus</td>
<td>Parts will be cut on water jet.</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Control Arms</td>
<td>B</td>
<td>1/8 in. 1008 Cold Roll Plate</td>
<td>Same Plate as Above</td>
<td>Water Jet Plate welded together</td>
<td>Need proper welding jig</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weld Bungs</td>
<td>B</td>
<td>1” Round Bar</td>
<td>McMastercarr</td>
<td>Lathe Welding</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heims</td>
<td>P</td>
<td>N/A</td>
<td>Purchased through PolyPerformance</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>Upright Body</td>
<td>B</td>
<td>1/8 in. 1008 Cold Roll Plate</td>
<td>McMastercarr</td>
<td>Water Jet Plate welded together</td>
<td>Need proper welding jig</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upright Dog Ears</td>
<td>B</td>
<td>5/8 Plate Steel</td>
<td>McMastercarr</td>
<td>This will be milled and bored for press fit swivel joints Post Welded to upright</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hubs</td>
<td></td>
<td>P</td>
<td>N/A</td>
<td>Purchased through ____</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steering</td>
<td>Rack</td>
<td>P</td>
<td>N/A</td>
<td>Purchased through Appletreeauto.com</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tie Rods</td>
<td>B</td>
<td>1 or 3/4 in DOM .120</td>
<td>Purchased through ____</td>
<td>Cut to size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brakes</td>
<td>Heims</td>
<td>P</td>
<td>N/A</td>
<td>Purchased through ____</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calipers</td>
<td>P</td>
<td>N/A</td>
<td>Purchased through Sponsor</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disks</td>
<td>P</td>
<td>N/A</td>
<td>Connection</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix K | Manufacturing Steps

**Upper Arm Fabrication**

- **Cold Cut Saw**
  1. Cut length of 1.5” tube down to appropriate size needed before use of Tube Shark. Need to leave excess for coping

- **Tube Shark**
  2. Follow bending instructions from Bend-Tech software to create curved profile

- **Waterjet**
  3. Cut top plate profile
  4. Cut COM joint bolt tabs

- **Dimple Die**
  5. Take waterjet plate and dimple die holes using arbor press

- **Weld**
  6. Weld prep. Clean up edges and get rid of contaminants
  7. Weld arms and plate together using welding jig

- **Notch Tube ends**
  8. Notch a slot in the end of the tube for suspensions tabs.

- **Weld Suspension Mounts**
  9. Weld suspension tabs for uprights
  10. Weld in threaded weld bungs for heims that connect to main chassis

- **Paint Prep**
  11. Get rid of mill scale and other contaminants with a combination of scotch bright wheels and acetone.

- **Paint Upper Arms**
  12. Steel-It paint job

**Lower Arm Fabrication**

- **Waterjet Profile**
  1. Waterjet the lower arm profile

- **Bend Plate**
  2. Bend plate in areas to complete the final profile

- **Weld Lower Arms**
  3. Weld prep Lower arms to get rid of contaminants
  4. Put stock in fixturing jig
  5. Tack arms
  6. Check squareness
  7. Weld as much as possible in jig
  8. Full weld

- **Weld in Weld Bungs Paint Prep**
  9. Get rid of mill scale and other contaminants with a combination of scotch bright wheels and acetone.

- **Paint Upper Arms**
  10. Steel-It paint job
**Subframe Fabrication**

- **Preparing Box Tube**
  1. This can be done on the cold cut saw or even on an abrasive saw. We will be cutting down to size our 3”x6” box tubes.
  2. Deburr sides

- **Waterjet Chassis Parts**
  3. Waterjet suspension tabs
  4. Waterjet gusset
  5. Waterjet shock tower
  6. Waterjet tube ties ins

- **Mill Box Tubes**
  7. Mill slots In box tube for suspension tabs

- **Weld Chassis Datum**
  8. Weld prep everything
  9. Use big welding table to tack box to table
  10. Weld suspension tabs to datum box
  11. Weld suspension tabs to secondary box
  12. Use waterjet gussets locate secondary plane
  13. Check for squareness and then full weld.

- **Bend Tubes for Bull Bumper**
  14. Cut 1.5” tubes down to reasonable size and bend using Tube Shark
  15. 45-degree miter ends of tubes for the buss bar
  16. Cut buss bar out of section of length and 45-degree miter

- **Welding Bull Tubes to Datum**
  17. Weld prep tube tie in plate, bull nose tubes and buss bar
  18. Tack tubes into tie in plate
  19. Tack tie in plate
  20. Tack in buss bar
  21. Check squareness
  22. Full weld tubes
  23. Remove tacks for tie in plate
  24. Full weld backside of tubes into tie in plate
  25. Realign tie in plate and tack adjust and full weld to datum box tube

- **Tube Tie-ins from secondary plane Box Tube**
  26. Cut and bend tubes with excess to cope
  27. Use Tube Master to create cope profile
  28. Use grinding wheel to slowly walk cope into fitment
  29. Weld prep tie in plate, and tubes
  30. Tack tie in plate to secondary box tube
  31. Fit tie in tubes up and tack to tie in plate only
  32. Check fitment and gaps and squareness
  33. Cut tie in plate to box tube tacks
  34. Full weld from backside
  35. Tack tie in plate back
36. Tack to bullnose tubes
37. Full weld everything else

- **Shock Tower**
  38. Weld prep shock tower
  39. Tack together shock tower
  40. Check squareness
  41. Full Weld
  42. Prep connection tubes cope/ miter tubes to fitment
  43. Tack tubes to datum then to shock tower.
  44. Use plumb bob to locate center point and check measurements before full welds
  45. Full weld

- **Paint**
  46. Prep all surfaces for paint using acetone and scotch bright
  47. Steel-It chassis

**Upright Fabrication**

- **Mill Tabs for Press fit**
  1. Depending on the stock we can waterjet and post machine which will be more efficient, or we can just machine these.

- **Waterjet Upright Profiles**
  2. Waterjet the upright profile to be welded

- **Bend Upright Profiles**
  3. Use press break to bend main upright profile

- **Welding Upright**
  4. Weld prep all material
  5. Insert parts in the jig for tacking
  6. Tack uprights
  7. Inspect geometry and other critical components
  8. Slowly full weld around to minimize warping

- **Paint**
  9. Test fit hubs before paint
  10. Paint prep as before
  11. Steel-It hubs

- **Arbor Press**
  12. Press and bolt in hubs

**Assemble Components**

1. Press bearings into uprights
2. Screw heims in welded bungs on lower and upper arms
3. Bolt heims into tabs on subframe. Use Delrin washers
4. Bolt uprights into arms using misalignment spacers
5. Bolt coil overs into lower arm and shock mounts on subframe
<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall Track Width Length</td>
<td>While the car is sitting at ride height, we will measure from one center point of the tire to the other center point of the tire.</td>
<td>Length (inches) 72 in +/- 5 inch</td>
<td>Tape measure</td>
<td>None</td>
<td>Dakota</td>
<td>5/12/2022</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Vertical Travel</td>
<td>Jog-up the rotation points of the arms connected by the upsets and mark the max extension and compression travel reaches once we have the actual joint hardware and shocks in hand.</td>
<td>Max vertical travel (inches) &gt;= 17 in</td>
<td>Tape measure</td>
<td>Simple (probably wood) jig, all heim and swivel parts, complete shock assembly, finished or mock-up arms and upright</td>
<td>Thomas</td>
<td>5/12/2022</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Maximizing Bump Shear</td>
<td>This can be visually tested by removing the springs and cycling the suspension. By mounting a laser to the hub and you can trace out the lasers travel on paper.</td>
<td>Degree/inch of Bump 0 +/- .1</td>
<td>Laser: Might be able to borrow from SAE</td>
<td>Full assembly tack-welded</td>
<td>Jimmy</td>
<td>5/12/2022</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Avoid yield failure in a 'worst case' realistic loading scenario of 3g landing + cornering, and braking marked out by traction</td>
<td>Perform quasi-static multi-body FEA on all components, by von-misses failure criteria</td>
<td>SF on all components</td>
<td>SF &gt; 2.0 on components</td>
<td>ANSYS student license still</td>
<td>None</td>
<td>Rebecca</td>
<td>2/24/2022</td>
</tr>
<tr>
<td>5</td>
<td>Welds stronger than base material</td>
<td>Tension test weld coupons, correlate weld strength with weld dimensions and visual inspection pass for analyzing the final prototype without destructive testing of finished components</td>
<td>Note if the base material fails before weld, weld dimensions, qualitative weld inspection notes</td>
<td>95% reliability after statistical analysis</td>
<td>Welding equipment in the Cal Poly shops, tensile test machine in the welding lab</td>
<td>Dakota</td>
<td>2/24/2022</td>
<td></td>
</tr>
</tbody>
</table>

Complete these columns when you conduct the tests.
Part IV: Final Design Report

For
Dave Schlossberg at Poly Performance

Presented By
James Ankers jankers@calpoly.edu
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On
06/07/2022
Abstract

This report provides a final update and conclusion to the senior project of four mechanical engineering undergraduate students at California Polytechnic State University, San Luis Obispo. This document follows three earlier deliverables, the first one being our Scope of Work document (SOW), that defined the project goal to be to design a long-travel independent front suspension system for Baja off-road racing enthusiasts to weld together and integrate on a Volkswagen Bug at a low cost. After that, concept development was performed, and a preliminary design report (PDR) was submitted. Using the feedback from our PDR we altered our design in various ways. We edited our CAD (Three-Dimensional Computer Aided Design), to reflect these changes and provided detailed descriptions and drawings of all parts to be fabricated. Next, we submitted a critical design review (CDR), which outlined the justification of our design, our manufacturing plan, and our design verification plan using various tests. In this report, our final design review (FDR), we outline how we manufactured the design and its various components. We then detail our testing procedures and comment on the success of our final design. We finish with concluding thoughts on our overall design process, what was successful and unsuccessful, and what recommendations we have for future improvement of the design. A user manual is included as Appendix A, for a potential customer of our kit concept.
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1 Design Updates

Our design was modified slightly since CDR, accommodating the thicker-walled bent tubes donated by our sponsor, change in part number for the threaded bungs to fit inside the new tube, and a corrected wheel hub bolt pattern. Additionally, we added weld tabs to all our welded plate parts in CAD to be readily cut with the waterjet and easily dry-fit for tack welding. Our updated CAD is shown in Figure 1.

![Modified Upright, with Weld Tabs and Corrected Bolt Pattern](image1)

![Final CAD Render, Demonstrating Maximum Extension on the Driver’s Side and Maximum Compression on the Passenger Side](image2)

*Figure 1 - Design Updates in CAD*

2 Verification Prototype Build

This section documents the procurement, manufacturing, and assembly of all components used in our final Verification Prototype build.

2.1 Procurement

Most of our design was custom-made in the Cal Poly machine shops, with the exception of bearings and assembly hardware which were purchased mainly from McMasterCarr.com and FK for their quality specifications and part CAD availability. We specified 12 in. King shocks, however, due to long wait times we were not able to purchase these shocks before the end of the school year. For the project expo we borrowed a Fox shock from the Baja racing team and in the future, the specified shocks will need to be purchased. Early in the quarter, our customer purchased a steering rack and wheel hubs, outside the immediate project scope of the project. While the steering rack has still not arrived, the hubs were able to be mounted on the final suspension build at the senior project expo.

For our raw steel material, we purchased a 4’x8’ piece of sheet metal from B&B Surplus in Santa Maria. In addition, our sponsor Dave Schlossberg donated some scrap 1.5” .180 OD 4130 tubing from Poly
Performance, which was oversized compared to our initial design, but the cost savings easily outweighed the desire for a lighter structure.

A summary of all donated and purchased parts and materials is included in Appendix B. Everything was directly purchased by our customer, Dakota Hollingsworth, with the $1500 set aside in the project bank account. Our final build successfully stayed within budget, with about $200 remaining.

2.2 Manufacturing
This section discusses the manufacturing methods used in the final Verification Prototype build, documents each component throughout its manufactured life, and describes any problems encountered or solutions found along the way.

2.2.1 General Manufacturing Processes
To avoid redundant description, our most common manufacturing processes are detailed here.

2.2.1.1 Water-Jet Cutting
A large portion of our parts were manufactured from water-jet steel plate, dry-fit with welding tabs for locating, and TIG fillet welded together. To start, the relevant faces for each plate were exported from CAD to .dxf files, the .dxf files were then imported into FlowPath software installed on the Mustang 60 water-jet computer, rearranged to make efficient use of the stock plate, and a cut file was generated and run, as shown in Figure 2.

![Water-Jet Ui, Shown Tracing the Cut Path](image1)

![Plates Being Water-Jet for the Upper and Lower Arms](image2)

Figure 2 - Water-Jet Cutting Process

2.2.1.2 Surface Preparation
Using scrap material and having outdoor storage meant the project required a lot of hours spent preparing the cut parts for welding. We used all kinds of methods to remove rust and scale, including wire-brushing, sanding with Dremels, and sandblasting the larger plate faces. If any surface impurities were left near the weld area, they could be pulled in and be the initiation site for a structural weld failure. Additionally, sharp edges had to be deburred, and weld edges beveled for consistent heat flow and weld penetration. Figure 3 illustrates these techniques.
2.2.1.3 Round Tube Operations

Figure 4 demonstrates the cutting, coping, and bending methods for modifying all our stock round tube into components for the subframe and upper arms.

Before using the TubeShark for bending pieces on our final build, the machine was calibrated according to the process described in Appendix D. This allowed us to know where to set the tube to compensate for a shifted start of the radius and magnitude of the radius, and how much to overshoot the desired angle to compensate for material spring-back.

2.2.2 Subframe Manufacturing

The subframe was manufactured in multiple parts, starting with rectangular subframe “core” that would serve as a datum and a mount for the other subframe components, followed by the shock tower, and finally the subframe was fully assembled with the round tube bull bar and other connections. The manufacturing of each component is further detailed in the following subsections, but the final subframe build is included here in Figure 5 for reference.
2.2.2.1 Subframe Core
The first step in manufacturing the subframe was to prepare the rectangular tube stock and tabs for accurately locating the arm pick-up-points relative to each other, depicted in Figure 6. The tube stock was simply cut to length and slots were CNC milled on either side of both parts. Bevels were added to clear space for weld material, and the surfaces were cleaned before clamping, squaring, and TIG welding around the 8 water-jet tabs on each tube, from the inside and outside of the rectangular tube.

Next, four water-jet plates were welded on to cap the ends of the two rectangular tubes to keep water and subsequent corrosion out of the inside of our parts. The result is shown in Figure 7.
With an equivalent preparation and weld process as used for the tabs, the water-jet side plates were welded to both rectangular tubes, shown in Figure 8. The slots in the side plates were cut with ¼ inch clearance on either side of the tabs, and the inside edges were beveled to clear the thick weld bead.

2.2.2.2  Shock Tower

The next major component in the subframe manufacturing was the shock tower. This was constructed with multiple water-jet plates held with clamps and TIG welded together, relying on gauge blocks and the weld tabs for squareness and locating, which are not super critical for this component. Additionally, some of our round tube stock was cut to length, slid into the water-jet holes, and welded in for extra stiffness. For fun, an icon of a Baja Bug was water-jet and tack welded to the front of the shock tower. The shock tower manufacturing is documented in Figure 9.
After any warping caused in welding, and to account for the fact that the shock tower round tubes have an incident angle to the plates that were cut two-dimensionally, a carbide deburring head on a Dremel was used to bevel the elliptical hole edges until the vertical round tubes could slide into place as shown in Figure 10a. With the shock tower aligned as shown in Figure 10b, the vertical tubes could be cut to length and finally welded.
place too easily while we worked with the alignment. The jigged alignment setup, and successful result are shown in Figure 11.

Unfortunately, the jig plate had to be held up at the correct position, and we had to check that it was centered by eye. This step got messy and time consuming, as pieces would move relative to each other. We could have further constrained the alignment with a vertical scrap wood plate that the horizontal jig plate could slot into, and have that set the height offset from the table.

A more advanced method would be to 3D print a jig that could replace all three scrap wood pieces and better constrain the centering and angle between tubes. A quick concept model of such a jig is provided in Figure 12, that could be refined by adding a matching top half that clamps or bolts together. This solution was not pursued in the interest of time and not consuming large amounts of plastic filament, but mostly we had not anticipated how difficult it would be to not have such a jig.

We might recommend trying a jig like this in the future, noting that the actual tube bends won’t be exactly like their CAD counterparts, and so would need to either be carefully measured or 3D-scanned, or large clearances should be used which would decrease the usefulness of the jig. Alternatively, the lack
of constraint we experienced in our alignment process did allow us the freedom to slide our design point around as the length and angles of our cut and bent parts aren’t very exact to the CAD, in an application where it matters more that the tubes come together with a structurally sound joint than having exact dimensions. Either way, this is a bit of a finicky step.

2.2.3 Upper Arm Mfg.
The upper arm manufacturing consisted of bending tubes and then welding on the gusset plate, weld bungs, and tab for the upright. The tubes were cut into sections and then bent using the Tube Shark. Once the front and back tubes were bent, the excess tubing was cut off. Next, in order to ensure accurate measurements, a full-scale drawing of the arms was printed. This drawing was taped to the welding table, and the arms were tacked onto the table above the drawing. Once both sides of the arms were fixed, they were welded together, as in Figure 13. After welding the two tubes together, a slot was cut for the upright tabs, and the bungs, tabs, and webbing plate were welded on.

![Bent Tube Portion of the Upper Arms, Shown Matching their Template](image1)

![Welding Upright Tabs on the Upper Arms](image2)

*Figure 13 - Upper Arm Manufacturing*

2.2.4 Lower Arm Mfg.
All the plates for the lower arms were water-jet from 1/8 inch sheet metal, and the tabs from ¼ inch material. The order of operations in welding the lower arm is essential for not blocking-off access to internal features or the back-side surfaces where weld tabs need to be welded into their slots. First, the upright tabs with their cross-plate were slotted into the bottom plate and were fillet welded all around. Then, the top plate was temporarily dry-fit for aligning the assembly, and was clamped in place for tack-welding the bottom plate and side plates. The top plate was then removed to weld in the threaded bung support plates, followed by the bung itself. The internal features are shown in Figure 14, while a broader view of the lower arm as it’s welded together is shown in Figure 15.
Figure 14 - Internal Features Welded to the Bottom Plate Before Closing the Lower Arm

Figure 15 - Inside and Outside Views of the Lower Arm During Welding
Separately, the shock mount plates were welded to the top plate, and the somewhat triangular reinforcement plate was slid over these plates and welded in place. The bottom plate partial assembly could then finally be welded to the top plate.

2.2.5 Upright Mfg.
The first step in manufacturing the uprights was to tack weld the reinforcing ring and hub nuts to the outer upright plate, using the purchased hubs as a template, as shown in Figure 16.

![Figure 16 - Purchased Hub being used as a Template for the Mating Pattern on the Upright](image)

The remainder of the upright manufacturing was very similar to the lower arms. Parts were waterjet and then assembled and welded. At this point, we had learned from the earlier bull bar alignment difficulty, and 3D-printed a jig to hold the many angled upright plates relative to each other during tack welding. Unfortunately, there was either slight shrinkage in the 3D printed plastic, or some disagreement between the CAD and actual upright parts, because the side plates could not fit and only the bottom surfaces and tabs were tacked together in the jig, shown in Figure 17a. The side plates and upper plate would then be aligned as shown in Figure 17b.

![Figure 17 - Tack Welding the Upright, With and Without the Jig](image)
Once the upright was welded together, the inside surface that pressed onto the hub had to be machined because the hub didn’t fit. This was done using the CNC Mill, and after that a snug fit was achieved between the hub and the upright.

2.3 Assembly

Once all the components were manufactured, they had to be painted. This was done using Steel-It, which is a weldable spray paint. That way, if any changes need to be done, or parts need to be fixed once the design is used, it will be easy weld. In addition, because the shocks have not yet been acquired, the shock tower was tacked on instead of full welded. This will allow for easier future adjustment if the shock tower is not perfectly aligned. Finally, all the components were bolted together, the bearings pressed into the uprights, and the heims installed on the arms. The completed project is shown in Figure 18.

![Figure 18 - Final, Assembled Verification Prototype](image-url)
3 Design Verification

Our design verification consisted of measurement tests to confirm the critical dimensions of our Verification Prototype, visual weld inspections to verify that our manufacturing methods are producing high quality welds, and tensile tests to confirm our weld and material structural capacities. A summary of tests conducted with their results is included as Table 1. Each test will be discussed in greater detail in the following subsections, the DVPR tables is included as Appendix C, and the test procedures with results are further documented in Appendix D.

<table>
<thead>
<tr>
<th>Test</th>
<th>Requirement</th>
<th>Result</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Travel</td>
<td>≥ 17 in.</td>
<td>17.4</td>
<td>Pass</td>
</tr>
<tr>
<td>Track Width</td>
<td>≤ 72 in.</td>
<td>76</td>
<td>Fail</td>
</tr>
<tr>
<td>Camber Gain</td>
<td>0 to -5 degrees</td>
<td>-2 to -6 degrees</td>
<td>Fail</td>
</tr>
<tr>
<td>Weld Inspection</td>
<td>No impurities, full penetration</td>
<td>No impurities seen. Weld appears to have penetrated the full material thickness.</td>
<td>Pass</td>
</tr>
<tr>
<td>Tensile Test</td>
<td>Welds stronger than base material</td>
<td>All three tensile specimens failed in the base material first.</td>
<td>Pass</td>
</tr>
</tbody>
</table>

The bump steer test is not included here, since it was removed from the project scope due to delays in the delivery of a purchased steering rack.

3.1 Dimensional Verification

Our first two dimensional tests of vertical travel and track width were simple measurements done with a tape measure, described in the Appendix D test procedures, and performed once the final design was fully manufactured and assembled. Unfortunately, the shocks did not arrive on time, so we had to substitute them for a ratcheting strap that we set to the relevant manufacturer-specified pin-to-pin lengths to simulate the maximum extension, compression, and mid-travel ride states. This set-up is illustrated in Figure 19. We confirmed a vertical travel of 17.4 inches, just over our 17-inch minimum target. Our track width was measured at 76 inches, wider than the desired 72 inch maximum, but this specification was low-stakes and built with healthy margin from the legal limit for a vehicle to be street-legal.

With the same ratcheting strap set-up, we used a digital angle gauge mounted on the outside upright face to measure the maximum bounds of our camber curve. This yielded measurements between negative 6 and negative 2 degrees, where the lower bound is just out of specification, from the acceptable negative five to zero range. Fortunately, the camber curves can be continuously refined by screwing the heim joints slightly in or out of the upper and lower arms.
3.2 Weld Inspection

To verify weld quality, we conducted a visual inspection test on some of our practice welded tube, as outlined in the Appendix D test procedures. In Figure 20, we see the cut open the welded joint where good weld penetration was achieved. The bead of the weld is an appropriate size, about the thickness of the material, and the weld went nearly all the way through the material. It is also important to note that the material in this test is thicker than the material we are using for our design, and it is easier to get better weld penetration with thinner material. Because of this, we are confident in our weld strength.
3.3 Structural Weld & Material Testing

This section describes how we structurally verified our weld quality and base material mechanical properties with tensile tests performed in the Aerospace Composites and Structures Lab on campus. Details of the test specimens and procedure are followed by qualitative and quantitative results, as well as uncertainty analysis to better understand the material yield strength.

3.3.1 Tensile Test Procedure

Since we didn’t have the time or financial budget for destructive structural testing of finished components, we instead selected to tensile test representative weld samples to verify that our manufacturing processes produce welds that are stronger than the base material. Having the base material fail first allows us to trust our structural calculations and finite element analysis that used properties of the base material and cross-section, which is a much easier analysis than characterizing the unpredictable material and irregular dimensions of actual welds.

For this test, we selected to pull three water-jet dog-bone test specimens with a transverse TIG double v-groove weld through the center, cut from the material stock used in the final build. The test specimen shape and test procedure were inspired by the ASTM “Standard Test Methods for Tension Testing of Metallic Materials” [1], though the inclusion of the transverse weld is not standard. Additionally, the dog-bone dimensions were scaled up for heat flow concerns when welding a narrow cross-section, and resultantly sat incorrectly in the jaws according to the American Society for Testing and Materials (ASTM) standard, but this did not appear to have changed the failure mode. A comparison of standard and actual test specimen dimensions can be found in Figure 21.

![Tensile Test Specimen Dimensions](image)

After the tensile specimens were manufactured, they were loaded and pulled according to the testing procedure provided in Appendix D. The testing set-up can be seen in Figure 22, and the specimens post-failure are shown in Figure 23, showing a high degree of plastic deformation.
15

**Figure 22 - Dog-Bone Specimen in the Instron Jaws Pre-Failure**

**Figure 23 - Visual Tensile Test Results**

a) Comparison of One Post-Failure Specimen to Two Pre-Failure Specimens,

b) Image of All Three Specimens Post-Failure, Illustrating In-Tact Welds and a Repeatable Ductile Failure Mode
All three specimens displayed ductile behavior, had very similar stress-strain curves, and failed in essentially the same way and at the same approximate location below the weld and outside the heat-effected zone. This was a successful test proving our weld quality.

### 3.3.2 Data Manipulation & Results

We are further able to investigate results through the load and extension information gathered by the system DAQ. Since strength was much more important for our design verification, strain gauges or extensometers were not used to acquire accurate strain and resultant elastic modulus data. Only the tensile force (in Newtons) and extension between the jaws (in millimeters) were output, and the stress-strain curve of Figure 24 was obtained through the \( \sigma = P/A \) (stress equal to axial force over cross-sectional area) and \( \epsilon = e/L \) (strain equal to elongation over initial length) mechanics of materials relationships, using the measured reduced cross-section dimensions and gauge length.

As depicted in Figure 24, our material yield strength was found to be 33.8 ksi, which is lower than the 50.8 ksi yield strength that our earlier structural calculations estimated. Coincidentally, our ultimate strength was found to be just over 50 ksi. This means that we now have only ensure a safety factor greater than or equal to 2.0 on ultimate, rather than yield failure. Fortunately, many of our components were built with thicker walls due to our team receiving thicker donated materials than we designed to, and the ductile material behavior will decrease the chances of unforeseen catastrophic failure. However, a re-run of the finite element analysis with true dimensions, and preferably static non-destructive deflection testing and destructive testing of final components are recommended for later steps beyond the scope of this senior project before any guarantees can be made.

---

**Figure 24 - Tensile Test Loading Plots**

\[ \sigma_y \approx 33.8 \text{ ksi} \]
3.3.3 Uncertainty & Error Propagation

To better understand our numeric results, we considered the propagation of individual measurement uncertainties through the mechanics of materials relations used to calculated yield strength, as well as the impact of having such a small sample size on our ability to predict the population behavior. The first uncertainty propagation analysis is based on Eq. 1, with calculations tabulated in Table 2.

\[
U_R = \pm \sqrt{ \left( \frac{\partial R}{\partial x_1} U_{x_1} \right)^2 + \left( \frac{\partial R}{\partial x_2} U_{x_2} \right)^2 + \ldots } \quad \text{Eq. 1}
\]

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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reading</td>
<td>Accuracy</td>
<td>Reading</td>
<td>Accuracy</td>
</tr>
<tr>
<td>1</td>
<td>0.1300 ± 0.001</td>
<td>0.7645 ± 0.001</td>
<td>3347 ± 16.7</td>
<td>± 200</td>
</tr>
<tr>
<td>2</td>
<td>0.1300 ± 0.001</td>
<td>0.7650 ± 0.001</td>
<td>3376 ± 16.9</td>
<td>± 200</td>
</tr>
<tr>
<td>3</td>
<td>0.1300 ± 0.001</td>
<td>0.7810 ± 0.001</td>
<td>3413 ± 17.1</td>
<td>± 200</td>
</tr>
</tbody>
</table>

Sources of uncertainty include the 0.001 in finite accuracy of the dog-bone width and thickness caliper measurements, the 0.5% load-cell accuracy on the Instron machine, and the ability to read the yield point from the load curve to about 200 lbf accuracy. The uncertainty propagation yielded about ± 2,000 psi on each of the yield strength calculations.

There may be a way to then use the distribution of the three measurements along with their individual uncertainties to predict the population, but it is absent from the Cal Poly Mechanical Engineering curriculum, so we selected to use the student-t chart method to characterise the population from a theoretical minimum data set of uncertainty subtracted from the nominal measurement, as well as a theoretical maximum data set of uncertainty added to the nominal measurement. We estimated the population mean and 99% confidence range for each set, according to Eq. 2, and conservatively arrived at the union of the two ranges as our final answer. These calculations are documented in Table 3.

\[
\mu = \bar{x} \pm \frac{ts}{\sqrt{n}} \quad \text{Eq. 2}
\]

<table>
<thead>
<tr>
<th>Statistical Term</th>
<th>Minimum Set</th>
<th>Maximum Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Mean, (\bar{x})</td>
<td>31728</td>
<td>35772</td>
</tr>
<tr>
<td>Sample Standard Deviation, (s)</td>
<td>161.8</td>
<td>191.8</td>
</tr>
<tr>
<td>Number of Measurements, (n)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Degrees of Freedom, (v = s - 1)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Confidence Interval, (P)</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Student-t Value, (t)</td>
<td>9.925</td>
<td>9.925</td>
</tr>
<tr>
<td>Population Uncertainty, (u)</td>
<td>± 927.3</td>
<td>± 1098.8</td>
</tr>
<tr>
<td>Population Min-Max Range</td>
<td>30801</td>
<td>36871</td>
</tr>
<tr>
<td>Population Mean, (\mu)</td>
<td>33836 ± 3035</td>
<td></td>
</tr>
</tbody>
</table>
With the combined uncertainty propagation and finite sample statistics, we finally estimate the yield strength of our steel material to be about 33.8 ± 3.0 ksi. Since we were already significantly off our earlier estimate, this 10% statistical range does not change our recommendations as discussed in Section 3.3.2.

4 Discussion & Recommendations

One thing that was made very clear during the design process was the importance of designing for manufacturability. Our first iteration of the design utilized mostly bent tubes, which would have been much more difficult to accurately manufacture. By using sheet metal and putting weld tabs in our design, we made the design much easier to manufacture. Another thing we learned was how large the uncertainty of our applied loads was. We ended up doing some FEA, but the majority of our material specifications were based on sponsor recommendations and word of mouth in the offroad vehicle community. If the budget and time were expanded in a continuation of this project, it would definitely be advised to gather accelerometer data from a similar vehicle on a desired course, run a multi-body FEA simulation to better understand the load sharing between components, and then conduct component-scale destructive stress tests.

Other next steps, if we were to continue the project, would be to purchase shocks and fully weld on the shock tower. After that, we would need to adjust the heims to slightly reduce the amount of negative camber of the design. If this is not sufficient, then the upright would need to be modified to change static camber of the system. The next possible change would be to decrease the track width of the design in order to attain the desired width of 72 in. This could be done by reducing the width of the subframe, or by completely redesigning the system.

Some manufacturing changes were implemented part-way through the manufacturing process. First, after having some trouble accurately cutting the bull bar, paper cutouts were wrapped around the rest of the tubes to correctly miter them. Another change introduced part-way through manufacturing was the use of the sand blaster. This reduced the difficulty of weld prep and made parts ready to paint, without having to remove as much mill scale post welding.

If the design was to be made for high volume production, some changes could be done to reduce the cost and make manufacturing easier. First, although we used a waterjet to cut all of our parts, for larger scale manufacturing, the parts would be laser cut. In addition, reducing the number of bent tubes would help make the design easier to manufacture. The use of more carefully designed jigs and fixtures could also be used, in order to ensure accuracy and repeatability. One possible jig was discussed in further detail in Figure 12 of the manufacturing section.

This Verification Prototype is a fully functioning design intended to replace the front suspension of a Volkswagen Bug. The design is a stand-alone system meant to be welded onto the roll cage of the vehicle. In addition, mating components such as a steering rack and brakes must be installed. A fully detailed description of the design, operation, and various maintenance procedures can be seen in the user manual in Appendix A.
5 Conclusion

Our design was to design a front suspension system for a VW bug and we were overall successful in achieving that goal. The main design specifications we considered were vertical travel and track width. The final design had a measured 17.4 in of vertical travel, which was above our desired 17 in. While this is a success it is important to note that we still need to bump and stop the design which will limit the travel beyond that number. In addition, our track width was 76 in. which was 4 in. larger than desired. When designing the system, we forgot to consider the width of the hubs which pushed our overall track width slightly too large. If we had to repeat the design, we would obviously try and fix these numbers. Ideally, we could obtain slightly more travel with a shorter track width, though this might take a complete redesign of the entire system.
References

Appendix A  | User Manual

This User’s Manual includes information, assembly & adjustment instructions, as well as important safety information. Read this section entirely, including all safety precautions, before use of the product.

**Note:** Manufacturing instructions will not be included in this User Manual. Fabrication of the components that make up this kit should be done by experienced fabricators, and require adjustment in construction to suit each individual chassis. For this reason, step by step instructions will not be provided, as if information contained in the Manufacturing Section is not sufficient, one should not be attempting to assemble this kit on their own.

**Warning:** This product is intended for off-road use ONLY. Before installation and use of this product, the user should be familiar with the risks and safety procedures associated with off-road driving and racing.

**Assembly of the Front Suspension**

**Warning:** All assembly should be done by an experienced mechanic who is confident in their own abilities and experience in setting up suspension systems. If the user is not confident in their mechanical abilities, they should contact a professional to assemble the kit for them, or to check their work at a minimum.

The following instructions include all necessary information required to assemble the front suspension and adjust wheel alignment to an appropriate range. It is assumed that the front subframe has already been fixed in the vehicle, via weldment attachment to the vehicle’s roll-cage. These instructions apply to just one side, procedure is the same for both sides.

**Control Arm Assembly**

Follow these steps to install and adjust lower arms:

1. Install Heim Joints & Jam Nuts to lower arms
   a. Ensure all threads (lower arm bung, Heim joint, and jam nut) are clean and clear of debris.
   b. Wrap Heim joint threads with 1-2 layers of Teflon thread sealant tape, to ensure snug fit between threads.
c. Thread jam nuts all the way down on Heim joints, until they bottom out on the shoulder of the joint, then loosen ½ turn.

d. Thread the Heim joint into the lower control arm, until jam nut is bottomed out against the threaded bung in the lower arm. Loosen the threads ½ turn, or until the Heim joint is oriented vertically as shown in the image above.

2. Install Lower Arm into Subframe
   a. Ensure both Heim Joints are oriented vertically as shown above
   b. Locate Delrin Washer on either side of Heim Joint, which should sit between the Heim Joint and the mounting tab, on either side (as shown below). Heim Joint should be completely insulated from the mounting tabs.
   c. Insert ¾” Bolt through tabs, apply red Loctite or (similar to) threads, torque to 45 ft-lbs.

3. Install Heim Joints to Lower Arms
   a. Ensure all threads are clean and clear of debris
   b. Apply 1-2 layers of Teflon thread sealant tape into Heim Joint threads
   c. Thread Heim Joints into upper arm, no jam nuts are required. Leave 1”-1.5” of thread protrusion on Heim Joints, which should be oriented vertically (as shown below).
4. Install Upper Arm into Subframe
   a. Ensure both Heim Joints are oriented vertically as shown above
   b. Locate Delrin Washer on either side of Heim Joint, which should sit between the Heim Joint and the mounting tab, on either side (as shown below). Heim Joint should be completely insulated from the mounting tabs.
   c. Insert ¾” Bolt through tabs, apply red Loctite (or similar) to threads, torque to 45 ft-lbs.

Upright Assembly

5. Assemble Upright
   a. Clean all surfaces including upright mounting tabs, COM-bearings, and misalignment spacers with acetone. All surfaces must be perfectly clean as assembly involves several press-fits and/or near to it.
   b. Press COM-Bearing into upright tabs (as shown below). To ease the process of pressing in bearings, one may freeze COM-bearing, and heat the upright ear into which it is being pressed. **WARNING:** It is not recommended to create a high heat differential between bearings and upright. Only heat upright ear to a max of 250 °F (any oven will work).
c. Install hub to upright
d. Insert misalignment spacers into COM-bearing on upright
e. Bolt upright to arms using supplied ¾” bolts, **apply red Loctite** (or similar) and torque to 85 ft-lbs. Orientation should be as shown below.
6. Alignment Adjustment

IT IS RECOMMENDED that alignment be performed on an alignment rack or another measurement method which guarantees consistent measurement. This section will not include instructions on how to measure alignment, only how to adjust. Adjustment procedure is same for ALL arms, driver and passenger, upper and lower.

1. Camber Adjustment
   a. Measure overall front camber. Static camber should be within -1° to -3°, depending on driver preference. **NOTE: Alignment should be measured with full vehicle weight applied, including driver, fuel, etc.**
   b. To increase front camber, Heim Joints on Upper Arm should be threaded out (more threads showing), and should be threaded in (less threads showing) on upper arm.
   c. To decrease front camber, Heim Joints on Upper arm should be threaded in (less threads showing), and should be threaded out (more threads showing) on lower arm.

2. Toe Adjustment
   a. Measure overall front toe. Static toe should be within 1/8” toe in, to 1/8” toe out, depending on driver preference. **NOTE: Alignment should be measured with full vehicle weight applied, including driver, fuel, etc.**
   b. To adjust toe, simply adjust turn buckle on tie rod.
## Appendix B  | Project Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty.</th>
<th>Source</th>
<th>Price</th>
<th>Is this a Discounted Price?</th>
<th>Final Total (Tax + Shipping)</th>
</tr>
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<tbody>
<tr>
<td>FKB-COM14T Spherical Bearing</td>
<td>4</td>
<td>Poly Performance</td>
<td>$15.00</td>
<td>Yes</td>
<td>$65.25</td>
</tr>
<tr>
<td>High Misalignment Spacer - 7/8 Bore</td>
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<td>Poly Performance</td>
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<td>$69.60</td>
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<tr>
<td>20' x 1.5&quot; x .188 4130 DOM Tubing</td>
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<td>Poly Performance</td>
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<td>$0.00</td>
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<td>Mustang 60 Machine Shop</td>
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<td>2005 Tacoma Wheel Bearing Hubs</td>
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<td>$146.76</td>
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<tr>
<td>3/4&quot; Hardware (Nuts, Bolts, Washers)</td>
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<td>Fastenal</td>
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<tr>
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<td>Apple Tree Auto</td>
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<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$1,301.69</strong></td>
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</tbody>
</table>
### DVP&R - Design Verification Plan (& Report)

<table>
<thead>
<tr>
<th>Test</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
<th>Numerical Results</th>
<th>Notes on Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall Track Width</td>
<td>While the car is sitting at ride height we will measure from one center point of the tire to the other center point of the tire.</td>
<td>Length (inches)</td>
<td>72 in +/- .5 inch</td>
<td>Tape measure</td>
<td>Full assembly at least tack-welded &amp; assembled</td>
<td>Dakota</td>
<td>5/26/2022</td>
<td>5/26/2022</td>
<td>76 inches (fail)</td>
</tr>
<tr>
<td>2</td>
<td>Vertical Travel</td>
<td>Jig-up the rotation points of the arms connected by the upright and mark the max extension and compression travel. Reaches once we have the actual pivot points of the arms and shocks in hand.</td>
<td>Height of the lower upright pivot point off the ground at maximum extension and maximum compression</td>
<td>&gt;= 17 in</td>
<td>Tape measure</td>
<td>Simple (probably wood) jig, all heim and swivel joints, complete shock assembly, finished or mock-up arms and upright</td>
<td>Thomas</td>
<td>5/26/2022</td>
<td>5/26/2022</td>
<td>55.25 in max height, 37.88 in min height, giving 17.38 in of travel (pass).</td>
</tr>
<tr>
<td>3</td>
<td>Camber</td>
<td>Jig-up the rotation points of the arms connected by the upright and magnetically attach the digital angle gauge to the outside upright face. Note the camber angle at maximum extension and maximum compression.</td>
<td>Camber angle of the outside upright face at maximum extension and maximum compression</td>
<td>5° &lt;= camber &lt;= 0°</td>
<td>Digital angle gauge in Mustang 60</td>
<td>Full assembly at least tack-welded &amp; assembled</td>
<td>Dakota</td>
<td>5/26/2022</td>
<td>5/26/2022</td>
<td>-6° at maximum compression (fail) and -2° at maximum extension (pass)</td>
</tr>
<tr>
<td>4</td>
<td>Minimizing Bump Steer</td>
<td>This can be visually tested by removing the springs and cycling the suspension. By mounting a laser to the hub and you can trace out the lasers travel on paper.</td>
<td>Degree/inch of Bump</td>
<td>0 +/- .1</td>
<td>Digital angle gauge in Mustang 60</td>
<td>Full assembly at least tack-welded &amp; assembled</td>
<td>Jimmy</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Welds stronger than base material</td>
<td>Tensile test weld coupons, correlate weld strength with weld dimensions and visual inspection questions for analyzing the final prototype without destructive testing of finished components</td>
<td>Note if the base material fails before weld, weld dimensions, qualitative weld inspection notes</td>
<td>95% reliability after statistical analysis</td>
<td>Welding equipment in the Cal Poly shops, Instron tensile test machine in the Aerospace Structures Lab</td>
<td>Three water-Jet dog-bone test specimens with a transverse TiG butt weld in the center, cut from the material stock used in the final build</td>
<td>Rebecca</td>
<td>5/19/2022</td>
<td>5/24/2022</td>
<td>All three welds passed the tensile test, since the base material failed first. The base yield strength was found to be 33.6 ksi, with 50 ksi ultimate strength, which is lower than our structural calculations estimated.</td>
</tr>
</tbody>
</table>
Appendix D | Test Procedures

The test procedures presented here are, in order,

1. Tube Shark Calibration
2. Track Width Measurement
3. Vertical Travel Measurement
4. Camber Gain Measurement
5. Weld Inspection
6. Welded Dog-Bone Tensile Testing

Test Name:
Test #1: Tube Shark Calibration

Purpose:
The purpose of this test will help us calibrate the tube shark. This test will reveal important numbers that will help us complete our final prototype without too many “hiccups”. With this we reduce the unknown information in order to not make errors during tube bending and waste our limited material.

Scope:
Calibration of the Tube Shark. Find Bend Offset, Spring Back of Tube and Achieved Bend Radius.

Equipment:
- Tube Shark
- Measuring Tape
- Digital Angle Gauge
- Paint Pen
- BendTech Software

Hazards:
- Pinch Points
- Slick Surfaces
- Sharp Metal Edges
- Pressurized Air

PPE Requirements:
- Safety Glasses
- Closed Toe Shoes
- Pants
- Long Hair Tucked Back
- Snag Points Removed (Hoodie Strings, Loose Long Sleeve Shirts, Rings, .etc)

Facility:
The Aero Hangar

Procedure:
1) Startup BendTech Software
2) Open Die Calibration Wizard
3) Cut and measure a piece of material.
a. Make sure the piece is long enough to create a 90 degree bend for calibration.

4) Mark the Tube a few inches from the end and enter into software.

5) This mark will be used as the starting point for all bends that can be easy aligned on the machine. We will later measure to figure out the bend offset from this position.

6) Bend Tube to 90 degrees.

7) We will need to bend the tube within 1 degree of 90 degrees. With our digital angle gauge, we will attempt to get in within .1 degrees. Make sure to liberate the tube to avoid kinking. We will be using motor oil.

8) Measure the part.

9) Measure the First leg. See Diagram.

10) Measure the second leg. This should be the one without the mark on it. See Diagram.

11) Check achieved angle

12) Place the part against a flat surface and check the angle of the bend using the digital angle gauge that was used to bend the tube. We expect to see the angle slightly less than the desired angle around 2-5 degrees. Make note of the difference and that would be the spring back angle for around 90 degrees. We previously have found that low angle bends around 20 degrees have spring back of around 2-3 degrees.

Results:
We do not have a pass/fail criteria. This test is being run to account for unknown information for the new tube die that was manufactured. We plan to run this test only once because it should give us all the information we need.

Test Date(s):
March 8th 2022 from 12 – 3 pm

Test Results:
- Achieved Center Line Radius (CLR): 6.24 Inches
- Calibrated CLR: 7.864 Inches
- Bend Location Offset: -4.135 Inches
- Spring Back: ~ 7 – 8 Degrees
- Distance from end of tube to mark: 9.25 inches

From this test we now determined what our achieved center line radius is. This will technically define what our tubes are bent to and would be different from what our CAD says. This means we should technically change our CLR by +0.24 Inches, but we do not think it will make a significant difference in our overall design and performance numbers. The real number we were after is the bend location offset. We chose to make all our bends start from the shoe that pulls the tube around the die on the most outwards face as seen below because it is very visible and easy to line up marks on. From this plane the start of our bend is – 4 and a 1/8 inches back. This will help us properly bend the tubes and help us not waste material. We were a little worried at first because of our new material thickness being so large, but the new die and tubeshark did quick work of making the bend. We also noted our spring back for the 90-degree bend. This was around 7 – 8 degrees. This value might change with shallower angles and be around 5 – 6 degrees. We might go back and try to get a better measurement to get a more exact bend offset.

Performed By:
Dakota and Jimmy
Test Name:
Test #2: Track Width Measurement

Purpose:
The purpose of this test is to see if we were within the 72 inch limit on track width.

Scope:
The scope of this test includes our entire design

Equipment:
We will need a measuring stick to measure the track width. In addition, we will need a flat surface such as a bench or table to constrain the subframe. We will used a rachet strap to simulate shock movement and take measurements where the arms are parallel to the ground.

Hazards:
The main hazard is pinch points, specifically where the upright meets the lower arm

PPE Requirements:
We will wear safety glasses because that is always necessary in the machine shops. Gloves should also be worn by the person doing the test because the main hazard is pinch points.

Facility:
The test will occur in the Cal Poly Machine shops

Procedure:
1) Fix the subframe onto a bench or table
2) Attach rachet strap to the pickup points of the shock.
3) Place the travel where the arms are parallel with the ground. We will find this by adjusting the rachet straps.
4) Measure the length of half of the design, from the center of the subframe to the face of the hub.
5) Double this measurement to obtain the track width measurement.

Test Date(s):
5/26/22

Results:
After measuring from the center of the subframe to the end of the arm, we obtained a measurement of 38 in. Doubling this we obtained a track width of 76 in. This is slightly larger than our desired value of 72 in. We realized that this is because we forgot to take into account the width of the hub when designing the system.
Performed By:
Dakota, Rebecca, Thomas

Test Name:
Test #3: Vertical Travel Measurement

Purpose:
The purpose of this test is to see if we obtained the 17 in of vertical travel that we were striving for.

Scope:
The scope of this test includes our entire design

Equipment:
We will need a measuring stick to measure the travel. In addition, we will need a flat surface such as a bench or table to constrain the subframe. We will also be utilizing a ratchet strap to simulate a shock.

Hazards:
The main hazard will be pinch points in the suspension.

PPE Requirements:
We will wear safety glasses because that is always necessary in the machine shops. Gloves should also be worn by the person doing the test because the main hazard is pinch points.

Facility:
The test will occur in the Cal Poly Machine shops

Procedure:
1) Fix the subframe onto a bench or table
2) Attach ratchet strap to the pickup points of the shock.
3) Place the travel into the full droop condition. We will find this by making the ratchet straps length the length of the shock at max extension.
4) Measure from the floor to a repeatable point on the lower arm. Ideally the center of the upright.
5) Place the travel into the full bump condition. We will find this by making the ratchet straps length the length of the shock at max compression.
6) Measure from the floor to the chosen repeatable point on the lower arm.
7) Take the two measurements and subtract them to get total travel of the suspension system.

**Test Date(s):**
5/26/22

**Results:**
In this test for our repeatable measuring point on the lower arm we chose the center of the bolt that connects the upright to the lower arm. Our first measurement was 37.875 inches off the floor. The second measurement was 55.25 inches.

When subtracting these two numbers we get 17.375 inches of vertical travel which is 3/8 of an inch more than we were aiming for. These number could change depending on what shocks are chosen by the customer due to the variation on compressed and extended lengths of the shock.

**Performed By:**
Dakota, Rebecca, Thomas
**Test Name:**
Test #4: Camber Gain Measurement

**Purpose:**
To measure the range of camber angles seen at the wheel between max extension and max compression, to verify that our design falls in the acceptable range of 0 to negative 5 degrees that maintains tire grip and cornering performance.

**Scope:**
This test will require at least the subframe core and shock tower, as well as one side of the suspension with upright to be tack welded and all hardware (including one shock) in place so that the full vertical travel can be seen.

**Equipment:**
- The subframe will need to be mounted on a stand or clamped to a table with a vice to prevent rotation that could affect the camber measurement and prevent falls.
- The measurement will require a digital caster/camber gauge that can be checked out at Mustang 60.

**Hazards:**
The main hazard is pinch points, specifically where the upright meets the lower arm

**PPE Requirements:**
Safety glasses should be worn around moving parts, closed-toed shoes should be worn as there could be a drop hazard, and the user should review potential pinch points when guiding the assembly through its full range.

**Facility:**
The test location is not important for this test, but it was conducted in the Mustang 60 machine shop.

**Procedure:**
To set up for our test, we used the largest vise in Mustang 60 to fix the subframe in position and allow for cycling of the suspension. We secured the vise by ratchet-strapping it to a pallet, as well as stacking 50-lb bags of sand around its base. We then used a digital level to measure the angle of our upright with respect to the stationary subframe. First, we used a tape measure and large ruler to pick several points throughout the sweep of the suspension at which to measure. Next, we zeroed the digital level on the flat center section of the subframe, and then moved the level to the upright, in order to measure the angle of the upright with respect to the subframe. Zeroing the level on the subframe itself before measuring the angle of the upright is important because it allowed us to ignore the positioning of the rest of the system with respect to the ground, which would be difficult to get perfect and introduce potential sources of error.

**Test Date(s):**
5/26/22

**Results:**
The results of our test were nearly perfectly ideal, as we measured 4 degrees of static camber, and 4 degrees of negative camber gain throughout the cycle of the suspension. At full droop we measured -2*, at full bump we measured -6*, and near mid stroke at ride height we measured -4*. Based on the
amount of adjustment we incorporated into our design, we can adjust the static camber around ± 4° total, which will allow us to achieve any alignment setting within the range that is commonly used in performance off-road driving. Considering this, our base setting of static camber is right where we want it to be, and more importantly, our dynamic camber curve is nearly perfect. This is a huge step in justifying our design as static camber can be adjusted if any error occurred in manufacturing, but the dynamic camber change of the suspension is relatively permanent, as it relies on the location of pivot points, not just arm length.

<table>
<thead>
<tr>
<th></th>
<th>Measured Value &amp; Accuracy</th>
<th>Qualification</th>
<th>Pass/Fail</th>
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<tr>
<td><strong>Minimum</strong></td>
<td>-6</td>
<td>≥ -5 deg</td>
<td>Fail, but this value can be</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>adjusted with pushing the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>hiems more outboard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bringing it into spec.</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>-2</td>
<td>≤ 0 deg</td>
<td>Pass</td>
</tr>
</tbody>
</table>

**Performed By:**
Dakota, Jimmy, Thomas
Test Name:
Test #5: Weld Inspection

Purpose:
This test is to ensure that we are creating welds that are structurally sound and lack contamination. If our welds are not to specification, they could fall outside the design parameters and cause a system failure.

Scope:
The scope for this weld test should embody all of our welded parts proving that we competent welders.

Equipment:
- The Weld Breaker (Baja tool designed for weld testing tubes)
- The Mill (if needed. We can potentially mill a tube in half, section cut, to check penetration on the weld)
- Bandsaw

Hazards:
- Long lever arms
- Potentially high energy objects becoming unconstrained

PPE Requirements:
- Eye Pro
- Face Shield
- Long Pants
- Closed Toe Shoes

Facility:
We will be conducting this test at the Hangar.

Procedure:
1) Using the Weld Breaker
   a. Obtain Eye pro and a face shield incase is anything slips out of the large vise
   b. Take weld coupon (our structural prototype) and insert into the large vise outside of the hangar doors
   c. Make sure the weld coupon is secure
   d. Place the Weld breaker over one of the branches of the structural prototype
   e. The weld breaker acts as a really long lever arm. It will make the steel yield and fail around the welded area
   f. What we expect to see is the tube to yield near the welded area. We should not see the weld fail. Look that the picture below to compare.
Examples of Passing Welds

![Sample #1 - Destructive Testing](image1)
![Sample #2 - Destructive Inspections](image2)

- Failure was not at the weld
- Failure was not at the weld
- Weld bead radius is approximately the same as tube wall thickness
- Wire / tube thickness was very small at point of failure
- Extreme heat discoloration

Examples of Failing Welds: Sample #1 (Destructive Testing)

![Cold Welds](image3)
![Hot Welds](image4)

- Failure was as the weld
- Failure was as the weld
- Poor fusion of the filler rod / wire to the tubes
- Little to no heat discoloration
- The fitted / coped edges of the tube are visible after separation

2) Using the Mill
   
   a. We will need to cut a tube in half with the bandsaw (Down the length)
   b. From there we will need to grab V block and a mill
   c. Machine the cut edge to clean it up
   d. From there we should get a clean view of the welded area and we can begin inspection
   e. We should see complete fusion of the material. Look at the picture below to compare
Test Date(s):
5/24/2022

Test Results:
We ended up having to go with the mill method with visual inspection, since we tried to break the welds to see if they would fail outside of the welded area and the tubing was too thick. We then created a new test procedure for tensile testing with an Instron machine to pick up what we were unable to accomplish with this test.
After cutting open the welded joint we can see that good weld penetration was achieved. The bead of the weld is an appropriate size, about the thickness of the material, and the weld went nearly all the way through the material. It is also important to note that the material in this test is thicker than the material we are using for our design, and it is easier to get better weld penetration with thinner material. Because of this, we are confident in our welds and their strength.

Performed By:
Dakota, Thomas

Test Name:
Test #6: Welded Dog-Bone Tensile Testing

Purpose:
This test is intended to verify that our welds are stronger than our base material, as well as find our material yield and ultimate strength, both to provide confidence in our earlier structural analysis.

Scope:
This test requires at least three water-jet and welded dog-bone specimens made with the metal, welding rod, and processes/equipment as used in the final built assembly. Further detail on the dog-bone specifications can be found in Section 3.3.1.

Equipment:
- Instron tensile testing machine with controlling computer
- Calipers or a micrometer for measuring the dog-bones

Hazards:
The main hazard in this test is the risk of sharp flying pieces as the tensile specimen breaks, though this risk is lessened since we’re working with ductile material. Additionally, there a potential pinch points around tightening the jaws and jogging the grip fixtures that the user should be aware of.
PPE Requirements:
- Safety glasses
- Closed-toed shoes
- Instron protective shield

Facility:
This test will be conducted in the Cal Poly Aero Department Structures and Composites Lab.

Procedure:
1) Power on the Instron machine and controlling computer.
2) Load Instron Bluehill software.
   a. Set up a test recipe by clicking New Sample > Select Method, and choosing a file from
      the desktop. Under the Method>Test Control>Test tab, assign the extension rate to
      3mm/min.
3) Measure cross-section dimensions near the weld center and document the welds and
   specimens via photograph.
4) Jog the grip fixtures to the approximate distance apart for the specimen length. Place specimen
   vertically centered between both jaws, and horizontally centered in the jaws. Ensure the part is
   reasonably vertically oriented to avoid buckling effects. Tighten down the upper jaws, then the
   lower jaws.
5) Lower the protective shield.
   a. **WARNING:** Do not begin the test without the protective shield in place. There is no
      sensor to verify the shield is in place, so the machine will not prevent you from getting
      hurt by test specimens breaking and flying across the room.
6) Under the Test tab, click the start icon, and the machine will auto-zero itself and begin the
   tensile test.
   a. Data will live-plot to the main window under the Test tab.
   b. At the start, you may see your load over extension plot increase nonlinearly, even
      though your material is well categorized as linear-elastic. This is due to slipping between
      the part and the jaws. If properly tightened, the plot will become as expected very soon.
7) Once the piece ultimately fails, the machine will automatically unload and display a red light
   labeled "TEST STOPPED." It is now safe to raise the protective shield, document the failure
   mode, and remove the specimen by loosening the jaws.
8) With the specimen removed, the "Return" button on the UI may be clicked to jog the grip
   fixtures back to their initial position before stretching the specimen.
   a. **WARNING:** Do not press return with the specimen still in the jaws. If it has not fully
      fractured into multiple pieces, this will introduce compression and the possibility for
      buckling failure that could send the specimen flying. If the specimen has fully fractured
      into multiple pieces, there is still the possibility the pieces will crash into each other or
      the jaws.
9) With the jaws returned to an appropriate position, the next specimen may be loaded, and the
   process repeated.
10) Once all specimens have been tested, you may click the "Finish" icon on the UI to save the plot data from all tests.
11) Power off the computer and the Instron machine.

Test Date(s):
5/24/22

Results:
All three welds passed the tensile test, since the base material failed first. The base yield strength was found to be 33.6 ksi, with 50 ksi ultimate strength, which is lower than our structural calculations estimated. Below are photos taken of the test samples.

Performed By:
Rebecca
### Appendix E | Risk Assessment

**designsafe Report**

<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment</th>
<th>Risk Level</th>
<th>Risk Reduction Methods /Control System</th>
<th>Final Assessment</th>
<th>Risk Level</th>
<th>Status / Responsible /Comments /Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-1</td>
<td>All Users Common Tasks</td>
<td>mechanical : crushing / Negligence</td>
<td>Serious Remote</td>
<td>Low</td>
<td>instruction manuals</td>
<td>Serious</td>
<td></td>
<td>/Crushing is really only possible with improper use of jack stands</td>
</tr>
<tr>
<td>1-1-2</td>
<td>All Users Common Tasks</td>
<td>mechanical : cutting / severing Sharp Edges</td>
<td>Minor Likely</td>
<td>Low</td>
<td>warning label(S), gloves, Debur parts</td>
<td>Minor</td>
<td></td>
<td>/Wear gloves when handling parts near cut edges</td>
</tr>
<tr>
<td>1-1-3</td>
<td>All Users Common Tasks</td>
<td>mechanical : drawing-in / trapping / entanglement Negligence</td>
<td>Serious Remote</td>
<td>Low</td>
<td>warning label(s)</td>
<td>Serious</td>
<td></td>
<td>/This is very unlikely. A combustion of things must go wrong before this occurs.</td>
</tr>
<tr>
<td>1-1-4</td>
<td>All Users Common Tasks</td>
<td>mechanical : pinch point Improper use, negligence</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>warning label(s), gloves</td>
<td>Moderate</td>
<td></td>
<td>/There is a very low chance of pinching when working on the arms. More of a risk when setting down material</td>
</tr>
<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Risk Reduction Methods / Control System</td>
<td>Final Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Status / Responsible / Comments / Reference</td>
</tr>
<tr>
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<td>--------------------------------------</td>
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<td>------------------------------------------</td>
</tr>
<tr>
<td>1-1-5</td>
<td>All Users Common Tasks</td>
<td>mechanical: head bump on overhead objects Negligence</td>
<td>Minor Likely</td>
<td>Low</td>
<td>instruction manuals</td>
<td>Minor</td>
<td></td>
<td>/This is if someone is working under the car. Bound to happen at least once.</td>
</tr>
<tr>
<td>1-1-6</td>
<td>All Users Common Tasks</td>
<td>Welding: uncontrolled ignition sources Improper Work Area, Flammable Objects Near Welding, Flammable Liquids Near Welding</td>
<td>Serious Unlikely</td>
<td>Medium</td>
<td>special procedures, standard procedures, instruction manuals</td>
<td>Serious</td>
<td></td>
<td>/make sure gas, acetone, other serious flammables are away while welding</td>
</tr>
<tr>
<td>1-1-7</td>
<td>All Users Common Tasks</td>
<td>Welding: hot surfaces</td>
<td>Moderate Likely</td>
<td>Medium</td>
<td>gloves, special clothing, footwear</td>
<td>Moderate</td>
<td></td>
<td>/Don’t touch hot stuff!</td>
</tr>
<tr>
<td>1-1-8</td>
<td>All Users Common Tasks</td>
<td>Welding: exposed electrical arcs During Welding Process</td>
<td>Minor Remote</td>
<td>Negligible</td>
<td>safety glasses, special clothing</td>
<td>Minor</td>
<td></td>
<td>/Wear your PPE and know who’s around you. Communicate before you start welding.</td>
</tr>
<tr>
<td>1-1-9</td>
<td>All Users Common Tasks</td>
<td>Welding: Inadequate Welds Total System Failure, Inexperienced</td>
<td>Catastrophic Likely</td>
<td>High</td>
<td>awareness barriers, warning sign(s), instruction manuals, video, on-the-job training (OJT), Hands on Experience</td>
<td>Catastrophic</td>
<td></td>
<td>/This is not a kit for a beginning welder. Make sure you get good welding experience before you attempt this project</td>
</tr>
<tr>
<td>1-1-10</td>
<td>All Users Common Tasks</td>
<td>heat / temperature: burns / scalds Touching Hot Welds</td>
<td>Serious Likely</td>
<td>High</td>
<td>standard procedures, safety glasses, footwear, special clothing, gloves</td>
<td>Serious</td>
<td></td>
<td>/Wear PPE. Don’t touch hot stuff!</td>
</tr>
</tbody>
</table>
In the risk assessment above there is a column that describes ways to mitigate the risks under Risk Reduction Methods. Below is a more detailed explanation of how to avoid or prepare for some of these risk and hazards. We wanted to first address the high-level risk then medium level risk.

**Risk Item # 1-1-9:** This kit could and will be dangerous for someone to use if they are not a confident welder. If this kit contains poor welding practices, then it is bound to fail within our range of loads. We recommend that you are comfortable on the welder and have some form of welding training.

**Risk Item # 1-1-10:** We want to make clear that it is important to be careful when welding. This involves letting parts cool properly, being mindful of where you touch your parts before and after a weld and as well as working around others. Serious burns can occur from touching hot metal. Please wear proper leather gloves for welding.
**Risk Item # 1-1-13:** While welding it is important to prepare your material before welding to curb any contamination and porosity from occurring. This involves cleaning your material with acetone. Since acetone is highly flammable and might be exposed to high temperatures while welding it is good practice to store the acetone as well as the rags used to clean the material far away from the place of welding. There are numerous reported accidents from experienced welders in the school shops of rags accidentally catching on fire because they are within the vicinity of the welder.

**Risk Item # 1-1-6:** While welding there is a chance for something in your surrounding area to ignite. Make note of materials that are within this area that are flammable. We advise that there is a fire extinguisher within reach of the welding area. Some items may be unavoidable such as the wall. We suggest welding on a metal welding table. Please be aware of your surroundings while working.

**Risk Item # 1-1-7:** Because you are welding you will be exposed to hot surfaces. To mitigate any burning again be mindful of what you are welding and where you have previously welded. Wear proper PPE. This would include a welding helmet, a cotton long sleeve shirt, cotton work pants, close-toed shoes. You should also not wear in any circumstance while welding synthetic clothing as it melts to the skin when it burns.

**Risk Item # 1-1-12:** While welding you want to be in a decently ventilated area. You also do not want to weld any stainless steel, galvanized steel or any painted or coated materials without proper ventilations systems and respirators. In this kit there will not be any of these include. You are working with other gasses. You want enough air to have proper circulation of the room. This can be leaving the garage door open or having a box fan in the side of the shop. There is also a place for too much ventilation where your shielding gasses are being blown away and allowing for porosity into the weld and oxidation. Be mindful of this because this can lead to weld failure.

**Risk Item # 1-1-14:** While welding you are being exposed to harmful and intense UV rays. Make sure you are welding proper welding PPE. Your welding helmet should be set to around 10-12 for a shade setting. Do not look at someone welding without a helmet. This can cause a sunburn on your eyes. Also be mindful when welding around others so they have time to prepare when you weld. Again, you should also be wearing long sleeve clothing and long pants to minimize exposed body parts to these UV rays.