Shell Eco-Marathon Urban Concept:

Front Suspension and Steering System Design

Final Report

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Executive Summary

The report below outlines the proposed steering and front suspension design for the Shell Eco-marathon team's vehicle. The scope of the project is defined by the rule book provided by Shell, which dictates certain requirements for each system. The scope is reasonably open, and mainly requires a steering system and front suspension system that function and fit with the chassis. The functional requirements of each system are based heavily on cost, ease of installation, and weight. The goal of each system design is to optimize each requirement to best meet the team's needs. The Shell rulebook shows basic requirements for the entire care, such as height, weight, and other specifics. For this project the rules being considered are those in the steering and suspension sections, which are all quite standard and leave room for creativity. Before selecting each type of system, alternative ideas were explored. For the steering system, a rack and pinion design, an arm joint design, and a ball joint design were considered. After evaluating each idea with a weighted matrix, the rack and pinion design was selected due to its light weight, cost and dependability. The final steering design uses the rack and pinion, but also explores spindle, control arm, wheels, hubs and brake designs. For the suspension system, leaf and coil springs, as well as driver seat and air suspension were considered. Using the same matrix system as a selection tool, the driver seat suspension system was selected, due to its simplicity. Although not a typical system seen in full size cars, for the scope of this project and the Eco-marathon event the suspension seat suits the car's needs. In addition to the seat, rubber pucks have been added between the spindles and the frame to dampen the vibration from the motor. Due to the smooth nature of the track, a full front suspension system is not required, the combination of the seat and pucks fit the needs of the vehicle. The car will experience various forces during the race, the largest sum of forces possible being the dynamic loading from hitting a large bump in the track, the dynamic loading from braking, and the dynamic loading from turning all occurring simultaneously. To ensure the steering system will not fail under these conditions, a thorough ANSYS analysis was done on the spindle mounting column, replicating the worst-case scenario with an additional 1.5 times factor of safety to represent the lower strength of the welds. The design passed by a large margin because of the combination of aluminum beams and steel bolts. The original budget for this designed system started at $1500 CAD, as the project progressed that became less and less feasible to meet the client's needs. After a meeting with the eco-marathon team, the total cost came out to $3900 CAD, which was accepted by the team. The closing of this project comes with four main deliverables in addition to this report: a detailed CAD drawing of each design, a parts list, an economic analysis (which has been included in this report), and full assembly instructions for the designed system.

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1.0 Introduction and Background

The Shell Eco-marathon is a global academic competition sponsored by Shell. The competition officially launched in 1985 with 25 teams competing in France and to date over 100,000 students from universities in over 60 countries have participated in the Shell Eco-marathon. This competition was created by Shell to bring to life their mission statement of providing more, cleaner energy solutions, working towards their goal for net-zero emissions. This competition gives those in STEM fields at university the change to work with alternative power sources. This experience can be crucial in getting current students interested in exploring alternative fuel sources and creating a more sustainable future.

The competition features different vehicle classes and different energy categories. These vehicles will compete on a closed track where their energy usage is monitored, with the goal of most efficient vehicle. The client, the Queen's Supermileage Design Team will be creating a vehicle to perform in the Urban Concept Class, and the vehicle will be in the battery electric energy category. The Urban Concept Class are for vehicles designed to consider city driving and must be built to consider human needs. Vehicles in this class will focus on stop and go driving.

The client will assemble the vehicle in-house using commercially available parts and parts specially manufactured as needed. A carbon fibre space frame designed with braided carbon fibre tubing connected with modular aluminum connectors and epoxy resin has been created as a SolidWorks model. The team is tasked to design the front suspension and steering systems for this vehicle. [1]

2.0 Project Definition and Scope

The bulk of the scope of this project comes directly from the "Shell Eco-marathon 2022 Official Rules" handbook. This set of rules directly outlines the guidelines for the race and specifically with respect to the two components being designed for this report, front suspension, and steering. The general goal of the project is to design a steering system as well as a front suspension system that fits well with the chassis and other components of the eco-marathon car.

With regards to steering, the rules state that "Vehicle steering must be achieved by one system operated with both hands using a turning motion. It must be precise, with no play or delay. Steering must be operated predominately through the front wheels." This must be achieved by a steering wheel with a minimum diameter of 250 mm, and bars, tillers, joysticks, indirect or electric systems are not permitted.

In the rulebook, the requirements for suspension have a wide scope, with the only caveats being that the system must be covered by the vehicle body.

Overall, the scope of this project requires functioning steering and suspension systems that meets the requirements of the rules while not causing additional problems for the team designing the chassis or back suspension. The local Queen's Eco-marathon team did not specify any direct deliverables outside of the rulebook. Deliverables for this project are detailed CAD drawings, a parts list, estimated costs, and assembly instructions.

3.0 Design Criteria and Functional Specifications

Design criteria are the customer requirements and are how the design alternatives will be measured against one another. The functional specifications are derived from the customer requirements; however, these are quantifiable metrics with numeric goals. These numeric goals will be denoted as the target and as the minimum requirement. These requirements are taken from the quality functional deployment (QFD) diagrams that can be found in the Appendix of this report. The customer requirements for the design can be found in Table 1 and the functional requirements which apply to the entire design can be found in Table 2. The values seen in the functional requirements were chosen from the clients stated requirements and Team 18's internal goals.

Table 1 – Customer Requirements.

Requirement	Definition
Affordable	Cost kept to a minimum to allow budget to be used more effectively.
Structural Stability	The steering system must be able to handle the loading from making a turn and handling the car.
Safety	The safety of the driver, the Queen's Supermileage Team, and all others involved in the Shell Eco-Marathon Competition is of the highest importance. This includes a lack of sharp edges on the parts, and modes of failure that result in the least danger for the driver and any others.
Easy to Assemble /Maintain	Ease of assembly and maintenance to allow the team to work effectively when out of shop.
Smooth	There should be no 'play' in the steering wheel, this is both dangerous and ineffective.
Lightweight	With an overall vehicle weight limit of 225 kg, minimizing weight wherever reasonably possible is extremely important.
System Integration	The system should not negatively interfere with other vehicle systems resulting in redesigns or unorthodox design. Ideally the system will positively affect other systems.
Follows shell rules	Shell has listed system requirements for the Urban Concept class and for general vehicle safety, these must all be followed.
Lasts throughout competition	The vehicle's lifespan is not long, being that it only needs to last for a single competition. Though the longevity of the system does not need to be high, the system must last through a single competition.
Ergonomics	The steering wheel must be comfortable to use for the duration of a race.
Handle Loading	The suspension system must be able to handle the loading from the mass of the vehicle, the driver, and forces applied during a turn.
Responsive	This relates to the travel of the suspension system and the time to return to original position after being affected.

Table 2 – Functional Requirements Relating to Both Systems.

Design Requirement	Definition	Target Value
Cost	The amount of money the systems designed cost.	Target: $1500 Minimum Requirement: $1800
Longevity	How long the vehicle can operate under sustained load.	Target: 100+ hours Minimum Requirement: 30 hours NOTE: Active run time of vehicle
Ease of Operation	How easy it is to operate the vehicle. Included driver comfort.	Target: 5 Minimum Requirement: 2 Based on subjective driver rating out of 5
Weight	Weight of the systems designed should be minimized.	Target: 35 kg Minimum Requirement: 45 kg
Number of Parts	The number of unique parts required to assemble the systems. Not including small hardware such as nuts, bolts, washers, cotter pins, ect.	Target: 20 Minimum Requirement: N/A
Number of Steps to Assemble	The number of steps required to assemble the system.	Target: 40 Minimum Requirement: N/A
Number of Tools Required	Amount of unique equipment and/or tools required to manufacture and assemble.	Target: 30 Minimum Requirement: N/A NOTE: Majority of tools and machinery required must be available in the McLaughlin Hall shop.
Time to Assemble	Time required to manufacture and assemble all parts.	Target: 20 hours Minimum Requirement: N/A NOTE: Must be assembled for testing before the competition at the end of the '21-'22 school year.
Interactions with Other Systems	Beneficial interaction with other systems/mechanisms.	Target: 3 Minimum Requirement: 0
System fail-safes	Design feature or practice to improve safety in the event of a system failure.	Must be able to keep the driver safe in the event of a system failure.

3.1 Steering System

In Table 3 below the functional requirements for the design which apply exclusively to the steering system can be found.

Table 3 – Steering System Functional Requirements.

Steering Specific		
Design Requirement	Definition	Target Value
System Friction	The amount of friction along the mechanical linkages from steering column to spindle steering arm.	Target: 40 N Minimum Requirement: 60 N [2] NOTE: Force measure at outer diameter of steering wheel.
Ergonomics	Ergonomics of the position and angle wheel relative to the driver.	Target: 5 Minimum Requirement: 2 Based on subjective driver rating out of 5.

3.2 Suspension System

In Table 4 below the functional requirements for the design which apply exclusively to the suspension system can be found.

Table 4 – Suspension System Functional Requirements.

Suspension Specific		
Design Requirement	Definition	Target Value
Loading capabilities	The optimal loading for the system.	Target: 400 kg Minimum Requirement: 350 kg Note: This is full vehicle weight; it is assumed there will be even weight distribution between the front and rear
Max Obstacle Height	The height of an object that the suspension system can overcome	Target: 3.5 cm Minimum Requirement: 2.5 cm

3.3 Eco-Marathon Rules

Meeting eco-marathon rules is a customer requirement for both systems. The rules themselves are a functional specification, but unlike the other specifications these rules will only have a single target value. For non-quantifiable rules the design either meets the requirement or does not. The applicable rules for the two systems can be seen in Table 5 below.

Table 5 – Shell Eco-Marathon Rules Pertaining to the Design of the Suspension and Steering.

Topic Area	Rules, Requirements and Specifications
General	• The total vehicle height must be between 1000 mm and 1300 mm • The total vehicle width, excluding rear view mirrors, must be between 1200 mm and 1300 mm • The total vehicle length must be between 2200 mm and 3500 mm • The maximum vehicle weight (excluding the Driver) is 225 kg. • Teams must submit technical drawings, photographs or animations of their entire vehicle design to the Organisers for approval at their earliest opportunity. • Results for Battery Electric vehicles will be expressed in kilometres per kilowatt hour (km/kWh), or miles/kWh depending on region, and will be determined by using a joulemeter supplied by the Organisers.
Steering System	• The vehicle interior must not contain any objects that might injure the Driver in the event of a collision. • Vehicle steering must be achieved by one system operated with both hands using a turning motion. It must be precise, with no play or delay. Steering must be operated predominately through the front wheels. • Steering must be achieved using a steering wheel or sections of a wheel with a minimum diameter of 250 mm. • The turning radius must be 6 m or less. The turning radius is the distance between the centre of the circle and the external wheel of the vehicle. The external wheel of the vehicle must be able to follow a 90° arc of 6 m radius in both directions. The steering system must be designed to prevent any contact between tyre and body or chassis • The Organisers reserve the right to set up a vehicle handling course to verify the following when the vehicle is in motion: driver skills, turning radius and steering precision

Table 5 – Continuation of the Shell Eco-Marathon Rules Pertaining to the Design of the Suspension and Steering.

Topic Area	Rules, Requirements and Specifications
Suspension System	• Urban Concept vehicles must have exactly four wheels that are in constant contact with the road. • The vehicle body must cover all mechanical parts when viewed from all sides. The wheels and suspension must be fully covered by the body when seen from above, and the wheels must be covered up to the axle centre line when seen from front or rear. The covering for the wheels and suspension must be a rigid, integral part of the vehicle body. • The vehicle must be equipped with a four-disc hydraulic brake system, with a single brake pedal, which has a minimum surface area of 2500 mm². The brake pedal must operate the master cylinders either directly or through a rigid mechanical link. Wires/cables are not allowed. Commercially available brake systems (discs and callipers) with a minimum disc thickness of 3 mm are mandatory. Manufacturer's documentation is required to demonstrate authenticity. Bicycle brakes are not allowed • The track width must be at least 1000 mm for the front axle and 800 mm for the rear axle, measured between the midpoints where the tyres touch the ground • The wheelbase must be at least 1200 mm • The rims must be between 15 to 17 inches in diameter • The wheels located inside the vehicle body must be made inaccessible to the Driver by a bulkhead and must not come in contact with the chassis or body. Any handling or manipulation of the wheels is forbidden from the moment the vehicle arrives at the starting line until it crosses the finish line.

4.0 Alternative Design Solutions

4.1 Steering System

Any type of power steering design is not viable in this scenario, as any compressor or motor would add to much additional weight to the system. This means all solutions must be designed with the appropriate mechanical ratio, so the system is not difficult for the driver to turn. The system starts with the driver's input from the steering wheel/column which is translated to linear motion and provide the input to the steering mechanism. The mechanism is comprised of the tie-rods, control arms, and stub-axles which are aligned using Ackermann steering geometry. This ensures that all the wheels turn about the same instantaneous center, which reduces tire rubbing during cornering. All the proposed steering designs consist of the same major connective components but differ in the joints used to translate the rotation of the steering column to the linear motion needed at the tie-rods. The tires, wheels, stub axles, and control arms will all be sourced parts which will interface with the chosen design at the bottom of the steering column.

4.1.1 Rack and Pinion

The rack and pinion design uses a bevelled pinion to drive a toothed bar, converting the rotational motion of the steering column to a linear motion at the wheels. The pinion is fixed to the end of the steering column and aligns with the teeth on the rack. This design is often enclosed in a case that protects the steering system and allows for easy installation. Rack and pinion steering systems are preferred in front wheel drive vehicles, as the rack and pinion case can be installed next to the transverse drive train [3]. This steering system is customizable to a very wide range of dimensions and loading requirements, and is a simple, rigid design solution. The main disadvantage of this steering system is that it can require a high force to turn the steering wheel depending on the mechanical advantage provided by the pinion. A diagram of a rack and pinion steering system is displayed below in Figure 1. [4]

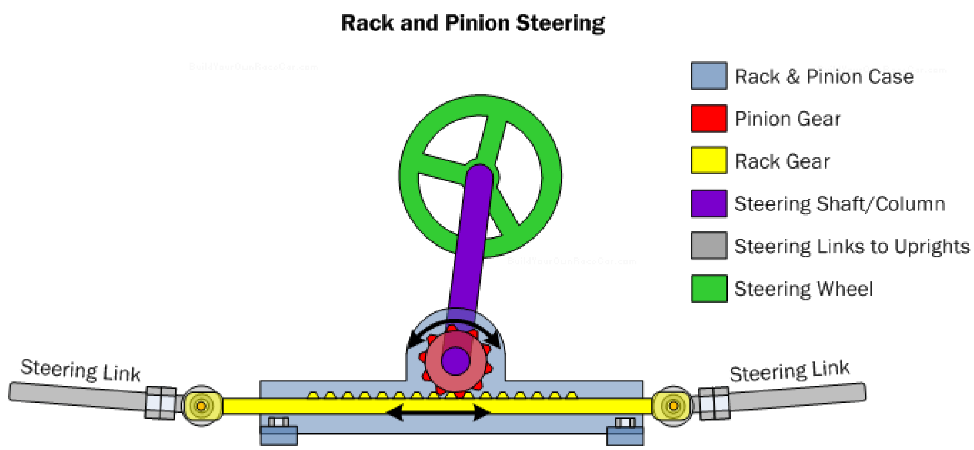

Figure 1 - Rack and Pinion Steering Design.

4.1.2 Rotating Arm Joint

The rotating arm joint design uses a “swing arm” to convert the rotational motion from the steering column to a linear motion at the wheels. This arm is fixed to the bottom of the steering column at one end and attached to two tie rods at the other. These tie rods connect to a linkage at the wheel hubs, turning the wheels as the steering column is turned. This design is very simple, cost effective, and light in weight. The simplicity of this design allows for easy installation and maintenance. However, the rotating arm joint design is more vulnerable to failure compared to the rack and pinion design and may not be as easy to integrate with other systems. An example of a rotating arm joint steering system is displayed below in Figure 2. [5]

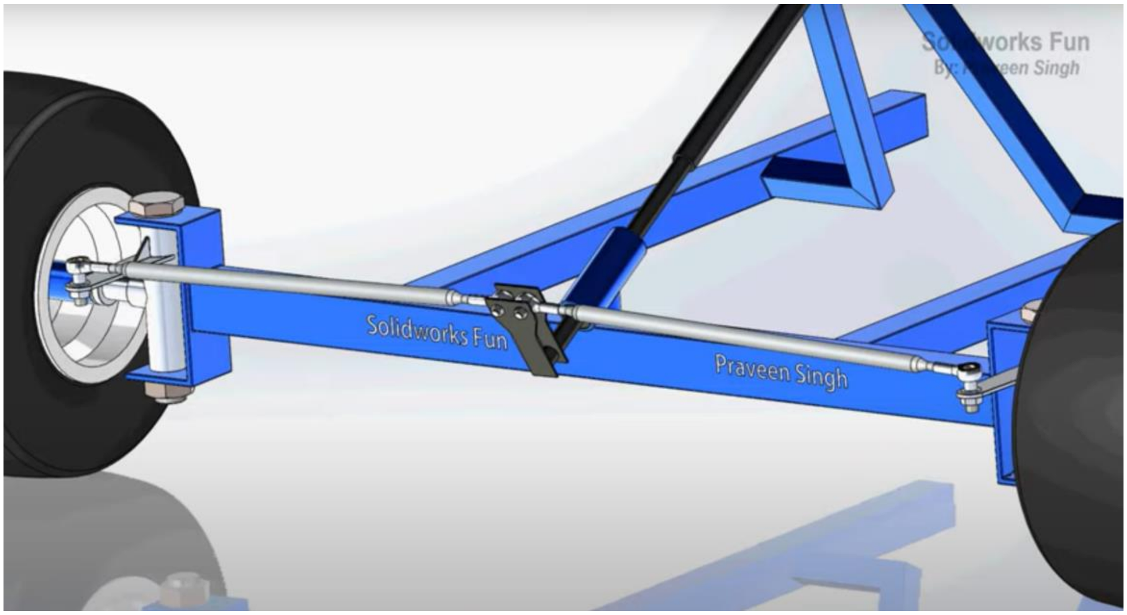

Figure 2 - Rotating Arm Joint Steering System.

4.1.3 Recirculating Ball Joint

The recirculating ball joint steering system uses ball bearings on a worm gear to convert the rotational motion of the steering column to the linear motion at the wheels. A rack encloses the bearings, which greatly reduce friction and ensures a tighter linkage. The main benefit of using this design is that it reduces "slop" which occurs when there are linkages that are not perfectly tight [6]. This allows for greater precision when turning and higher durability of the system. However, the disadvantages of this design are that it is heavy and there are many wear points due to the complexity and number of linkages [7]. The recirculating ball joint design is pictured below in Figure 3. [6]

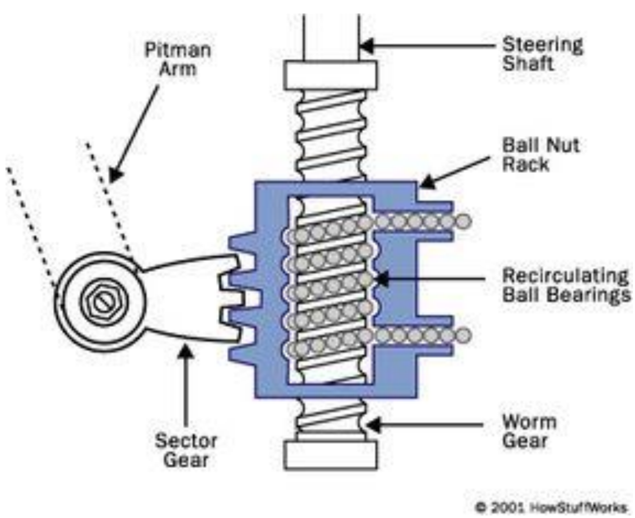

Figure 3 - Recirculating Ball Joint Steering System.

4.2 Suspension System

Based on research in the previous report, it was found that there are four main types of suspension used in vehicles: leaf springs, coil springs, torsion bars and air [8]. Since the scope of this project only covers front suspension, torsion bars were ruled out due to their spacing requirements. As a fourth option, a suspension system for the driver's seat was analyzed. Each type is described in detail below.

4.2.1 Leaf Spring Suspension

Leaf spring suspension is the oldest type of suspension. It is made up of layers of steel of varying sizes that flex when pressure is added, before returning to its initial position when the pressure goes back to normal. It rests below the axel using large U-bolts to secure it in place [9]. Figure 4 is an image of a vehicle with a leaf spring suspension system [8].

Figure 4 - Leaf Spring Suspension System.

4.2.2 Coil Spring Suspension

Coil springs are a spiral of resilient steel rod that deflect when pressure is added (going over a bump for instance). The coil alone could continue to bounce up and down depending on the situation. To reduce the undesired bounce effect, the coils are paired with dampers (shock absorbers) that slow down the spring oscillations to return the vehicle to a level ride quicker [10]. Figure 5 is an image of a vehicle with a coil spring suspension system [8].

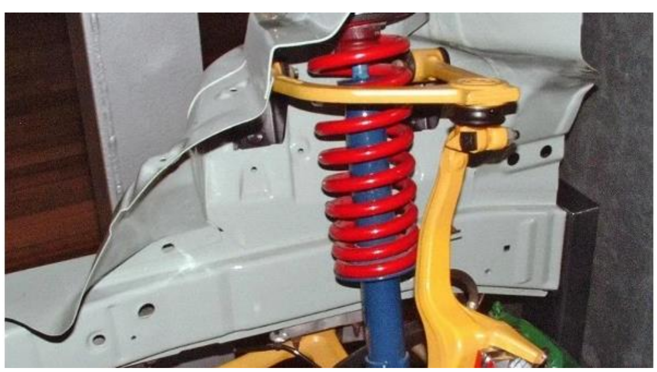

Figure 5 - Coil Spring Suspension System.

4.2.3 Driver Seat Suspension

As its name suggests, only the driver seat will benefit from the suspension. It works by having a liner suspended between a steel frame. As the occupant moves up and down, the liner gives, preventing the body from constantly hitting against a hard surface. Figure 6 is an image of a seat that uses this technology, outlining the various components it uses [11].

Figure 6 - Driver Seat Suspension System.

4.2.4 Air Suspension

Air suspension is made of pressurized flexible rubber bellows that act as springs (called air springs). Known to be a smoother, more modern type of suspension. With the use a compressor, air dryer, and air reservoir, the air pressure and ride height can be adjusted to provide optimal ride quality [12]. Figure 7 is a graphic of an air suspension system.

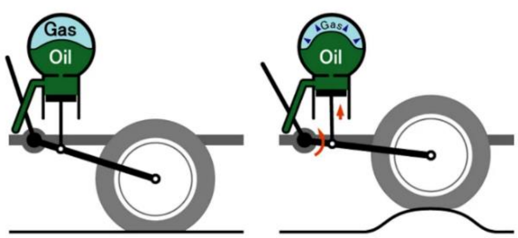

Figure 7 - Air Suspension System.

5.0 Design Evaluations

To compare and evaluate the proposed designs, Table 6 and Table 7 were created. These tables are evaluation matrices based on the demanded qualities of each system's QFD created in the previous report, seen in Figure 25 and Figure 26**.** Each design was scored as a whole number out of five for every demanded quality, with five being the best score. The results were then multiplied by the demanded quality's weighted importance values determined in the previous report. Finally, the results were summed up for each design at the bottom of the tables, with the highest scoring design being the best option.

5.1 Steering System

Table 6 - Evaluation Matrix for the Alternative Steering System Designs.

		Rack and Pinion		Rotating Arm Joint		Recirculating Ball Joint	
Demanded quality	Weight (%)	Mark	Score	Mark	Score	Mark	Score
Affordable	6.3	4	25.2	5	31.5	3	18.9
Structural Stability	12.5	4	50	2	25	5	62.5
Safe	12.5	4	50	3	37.5	4	50
Easy to assemble/maintain	7.8	4	31.2	5	39	3	23.4
Smooth	4.7	4	18.8	3	14.1	5	23.5
Lightweight	12.5	3	37.5	5	62.5	2	25
Positively integrate with other systems	10.9	4	43.6	3	32.7	2	21.8
Follows Shell rules	14.1	5	70.5	5	70.5	5	70.5
Last throughout competition	14.1	4	56.4	3	42.3	5	70.5
Ergonomics	4.7	4	18.8	4	18.8	4	18.8
Total	**100**		**402**		**373.9**		**384.9**

5.2 Suspension System

Table 7 outlines the scoring of each design for every demanded quality for the front suspension system. Leaf spring and air suspension ranked the lowest, while coil spring and driver seat suspension scored much higher. Driver seat suspension achieved the greatest score, beating coil spring by a small margin (scored only about 3.2 % higher). The reasoning behind the scores achieved, and the proposed design choice is discussed in detail in section 6.2.

Table 7 - Evaluation Matrix for the Alternative Suspension System Designs.

		Leaf Spring		Coil Spring		Suspension Seat		Air	
Demanded quality	Weight (%)	Mark	Score	Mark	Score	Mark	Score	Mark	Score
Affordable	4.3	3	12.9	4	17.2	4	17.2	1	4.3
Handle the loading	13	5	65	5	65	5	65	5	65
Safe	13	5	65	5	65	5	65	5	65
Easy to assemble/maintain	7.2	4	28.8	3	21.6	5	36	2	14.4
Smooth (minimal jerk)	2.9	2	5.8	4	11.6	3	8.7	5	14.5
Lightweight	13	3	39	4	52	4	52	1	13
Positively integrate with other systems	11.6	3	34.8	4	46.4	5	58	3	34.8
Follows Shell rules	13	5	65	5	65	5	65	5	65
Last throughout competition	13	5	65	5	65	5	65	5	65
Responsive	8.7	2	17.4	4	34.8	3	26.1	5	43.5
Total	**100**		**398.7**		**443.6**		**458**		**384.5**

6.0 Proposed Design

6.1 Steering System

Using the evaluation matrix for the steering system seen in Table 6, it was concluded that the best design for this application would be the rack and pinion steering system. The main reasons this design was chosen over the others was because it is relatively inexpensive and light in weight, while still maintaining structural stability and precision. The steering system will be composed of eight main components: the rack, pinion, rack and pinion case, tie rods, steering column, steering wheel, wheels, and tires. Supplementary components such as brackets and bearings are also required to allow for mounting, linkage connections, and supporting the weight of the vehicle. Hardware is required for the assembly of the steering system; it is available in the McLaughlin shop.

The tire, wheel and stub axle assembly are to be mounted on pivot points on the vehicle frame. The wheels are then oriented by the control arms being connected to the tie rods, which connect to the rack and pinion which connects to the steering column.

6.2 Suspension System

Based on the evaluation matrix seen in Table 7, it was determined that a driver seat suspension system should be used. Looking at the alternatives, air and leaf spring suspension ranked the lowest. Leaf spring fell short due to its greater weight, size, and poor responsiveness relative the alternatives. Similarly, air suspension ranked poorly due to its greater cost, weight, and size. Many of the upsides for air suspension, such as its superior smoothness and adjustability, are not as important in the scope of this project.

Coil spring and driver seat suspension both recorded relatively high scores, with the driver seat suspension winning by a small margin. This is mainly due to the simplicity of the design. Adding a coil spring suspension system would not integrate as well as it adds complexity to the steering system, whereas the driver seat suspension would have no effect on it. Additionally, while the driver may experience more comfort with the coil spring system, the vehicle does require much driving time and it is supposed to be tested on a relatively smooth track course, meaning the extra comfort does not add much value to this project.

After much deliberation it was determined that the vibrations from the track due to having no front suspension may still have some effects on the system despite the fact the vehicle will only be operating for short period of time on a relatively smooth test track. To ensure that the vehicle lasts throughout the entire competition, in addition to the suspension seat, dampening pucks are proposed to be implemented in the steering system.

7.0 Final Design

After the general design concepts were determined, and many design iterations were completed, the final designs were determined. This section details the final designs for the steering and front suspension systems.

7.1 Suspension System

The final suspension system design consists of two separate systems: the suspension seat and the vibration dampening pucks. The suspension seat is intended to provide added comfort for the driver to help them achieve their best possible performance, while the vibration dampening pucks are intended to dampen some of the vibrations coming from the front wheels to improve the vehicle's longevity.

7.1.1 Suspension Seat

The proposed suspension seat design is comprised of two main components: a suspension seat, and two aluminum beams to be welded to the bottom of the chassis, as seen in Figure 8, to support and mount the seat. The beams also provide more rigidity for the entire vehicle as well as offer more support for the suggested plywood floor design created by the chassis team last year. Additionally, it is a much safer alternative to mount the seat to the beams rather than directly to the plywood floor.

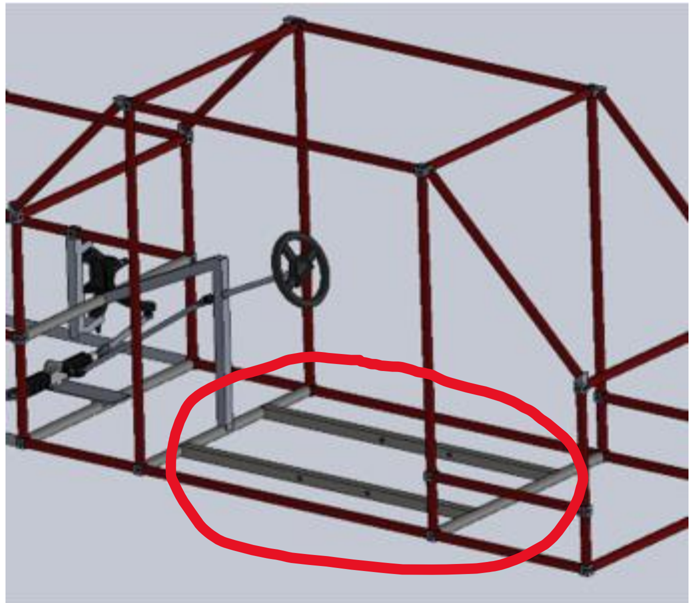

Figure 8 - Annotated Screenshot of the Final CAD Design Highlighting the Two Support Beams Added to the Chassis for the Seat.

To mount the seat to the bars, a hole the same size as the hole in the mounting brackets that come with the seat, as seen in the bottom of Figure 9, should be drilled through the beams. To secure the seat to the beams four bolts placed through the holes in the beams and seat mounting brackets secured with washers and nuts are to be used. Unfortunately, the seat's website does not specify the dimensions of the seat's mounting bracket holes so the bolts should be purchased after the seat arrives to ensure an ideal bolt is selected. The suspension seat, bolts, washers, and nuts can be purchased online, while the beams must be custom made and welded to the chassis.

The seat should be mounted in the center of the vehicle since only one person, the driver, is required to be in the vehicle. Placing it in the center benefits the steering system as it reduces its complexity since having the steering wheel in the center means both sides of the system would be symmetrical. The vehicle also would not be able to accommodate two seats as the suggested seat to be purchased is 558.8 mm (22") wide while the width of the chassis is 800 mm [13]. The height of the chassis is 1100 mm and the height of the seat from its lowest mounting point to the top is 787.4 mm (31") [13]. This leaves plenty of room above the driver's head, over 300 mm, to account for the minimum requirement of 50 mm of space between the driver's helmet and the top of the chassis.

Figure 9 - Image of the Suspension Seat to be Used that Outlines its Dimensions.

7.1.2 Vibration Dampening Pucks

Because of the nature of the track, there are very few bumps or uneven spots that would appear on a normal road. This allows for a simplistic front suspension design. The suspension system is made up of the seat outlined above and vibration dampening rubber pucks. These pucks are a similar size and shape to a washer and are to be placed atop each spindle. The pucks are made of vulcanized rubber, a material that is elastic and very weather resistant. The addition of this rubber will dampen vibration throughout the spindle and entire steering system. Although the surface of the track is quite smooth, the motor and tires will provide shaking which could result in damage to the aluminum. The location of the rubber puck can be seen in Figure 10.

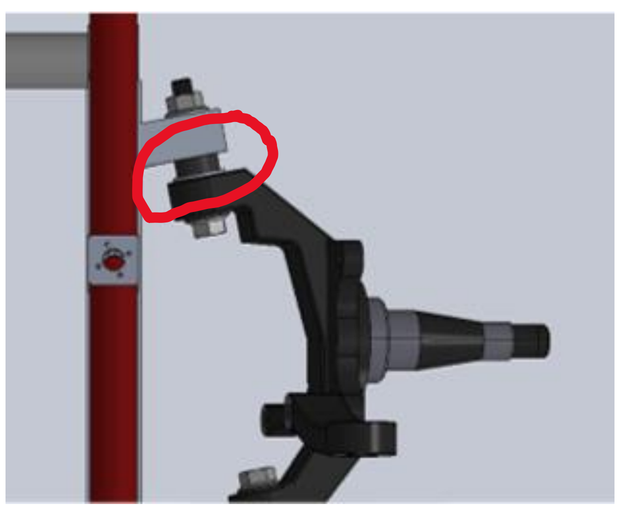

Figure 10 - Zoomed in Annotated Screenshot of the Final CAD Design Highlighting the Rubber Vibration Dampening Pucks Integrated at the Top of Each Spindle.

7.2 Steering System Overview

The final steering system design is as follows. The steering system is supported by the shown additional support members which are welded to the aluminum frame members. Manufacturing details and assembly instructions for all parts and aluminum frame members, are included in the Assembly Instructions. The steering geometry is able to reach a steering angle sufficient (>21°) to meet the maximum turning radius requirement of 6m.

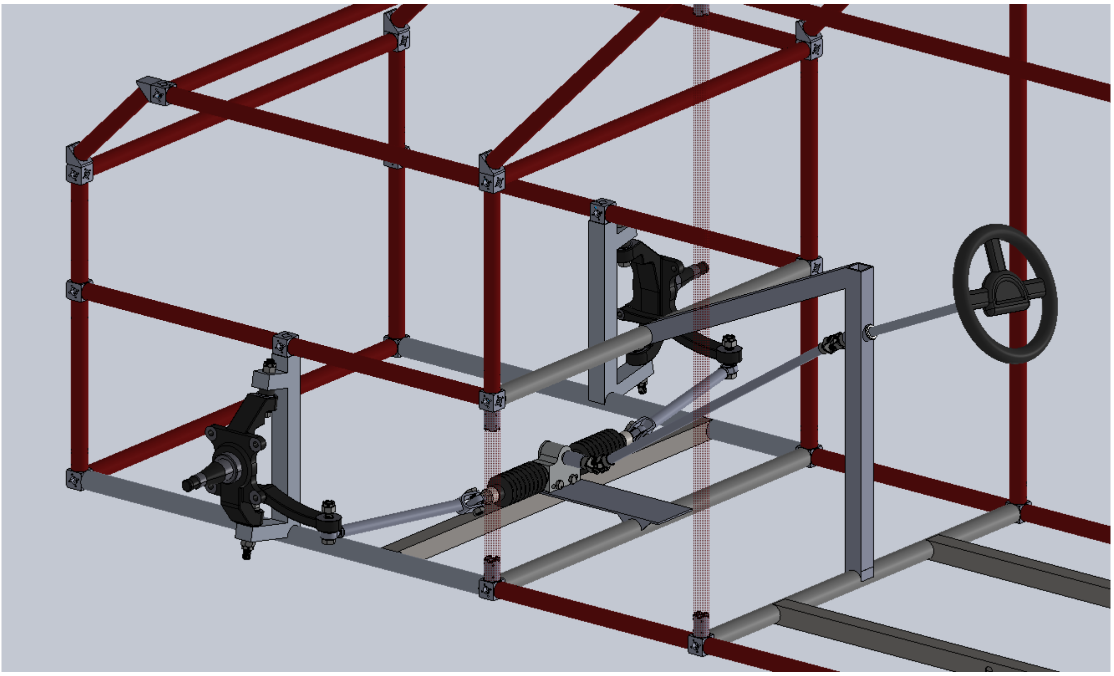

Figure 11 - Steering System Final Assembly.

7.2.1 Spindle and Control Arm Mounting

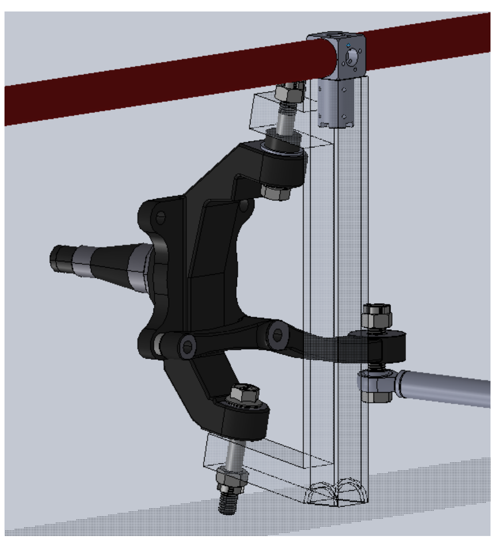

Figure 12 - Spindle Frame Mount.

The spindles are mounted to aluminum uprights which are welded to Beam A on the bottom and fastened to the frame connection on the top. The spindle mount has to conform to the mounting dimensions of the spindle. The required dimensions of the spindle mounts are shown in Figure 13, with emphasis to be placed on the mounting holes being axially aligned, so that the spindle may mount properly. The control arm is included in the spindle package and is connected via screws and offset washers. Failure analysis on this major structural component can be seen in section 8.

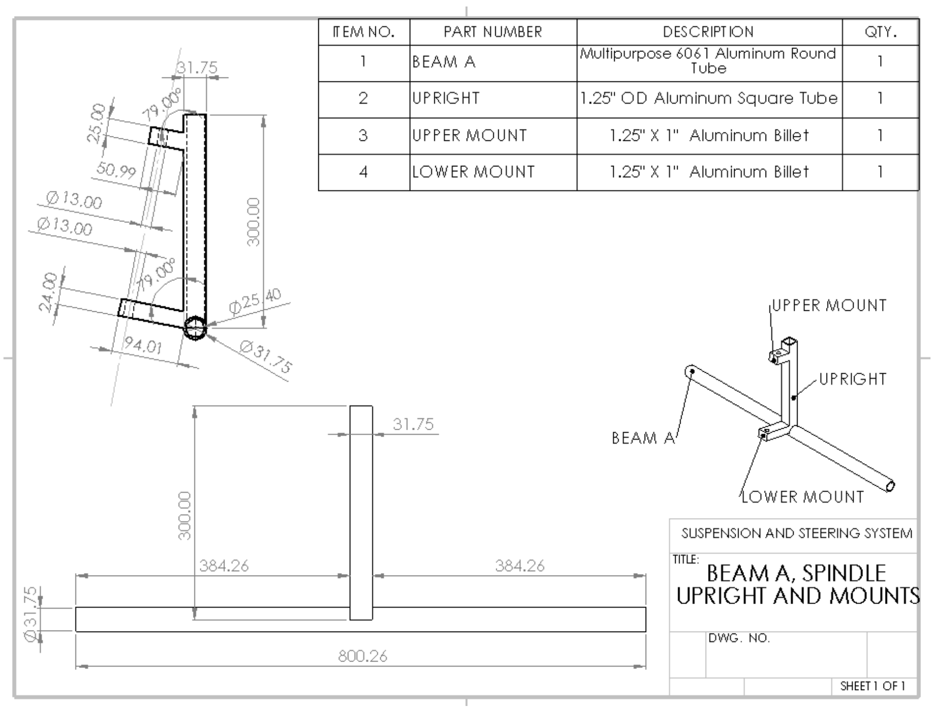

Figure 13 - Spindle Mount Dimensions Showing Position and Alignment of Mounting Holes and Members.

7.2.3 Tie Rods, Rack and Pinion and Steering Column

The steering column is composed of the steering wheel mounted to the quick release adapter which connects to the top of the steering column. The steering column is supported by a nylon bushing mounted in the support member and two universal joints transfer the rotational motion through the shafts down to the rack and pinion (Figure 14). The rack travels linearly with the rotation of the pinion. The tie rods connect the rack to the control arms of the spindle assemblies which complete the transfer of the rotational motion from the steering wheel to the articulation of spindle, thus the wheel assembly. The motion can be seen in the provided CAD assembly as the mechanical mates are all functional for the steering assembly. All components and linkages are explained and referenced in the Assembly Instructions and the Parts List. Note that the functional geometry in the assembly is correct but part models for the steering linkages are approximations of the recommended components included in the steering assembly kit and the tie rod kit, for detailed instructions see the Assembly Instructions.

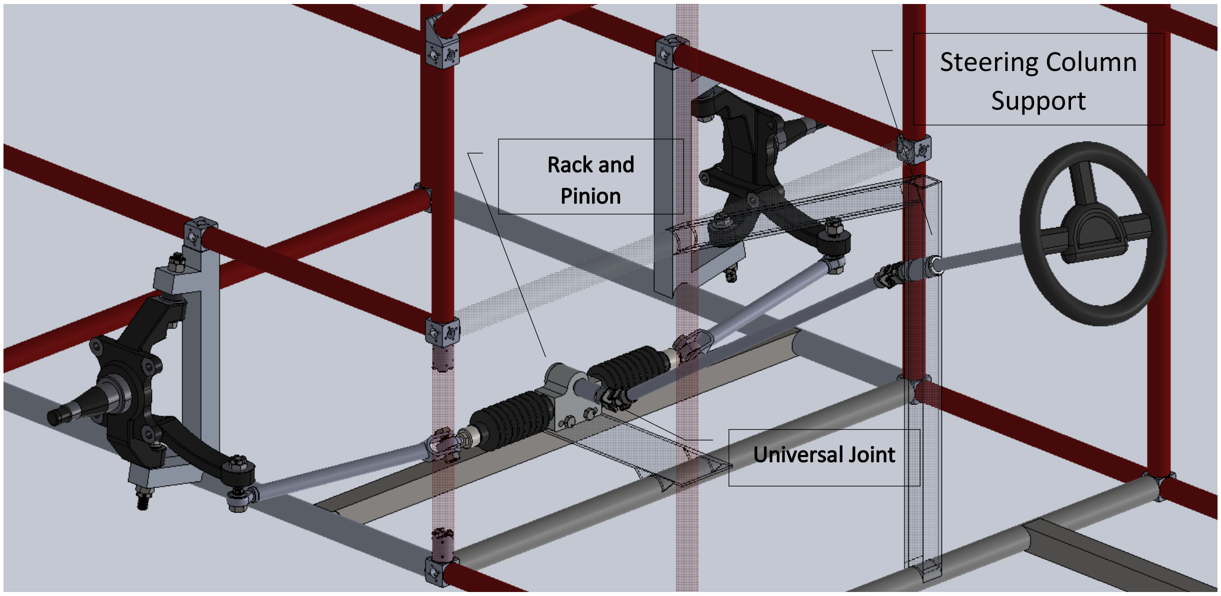

Figure 14 - Steering Column and Linkage Assembly.

7.3 Wheel, Hub and Brake Assembly

The Wilwood Dynalite front brake kit is designed for use with the Mustang II ProSpindles, and a detailed assembly detail is shown. Detailed assembly instructions are available in the Assembly Instructions and links to manufacturer's details and assembly instructions are included in the Parts List.

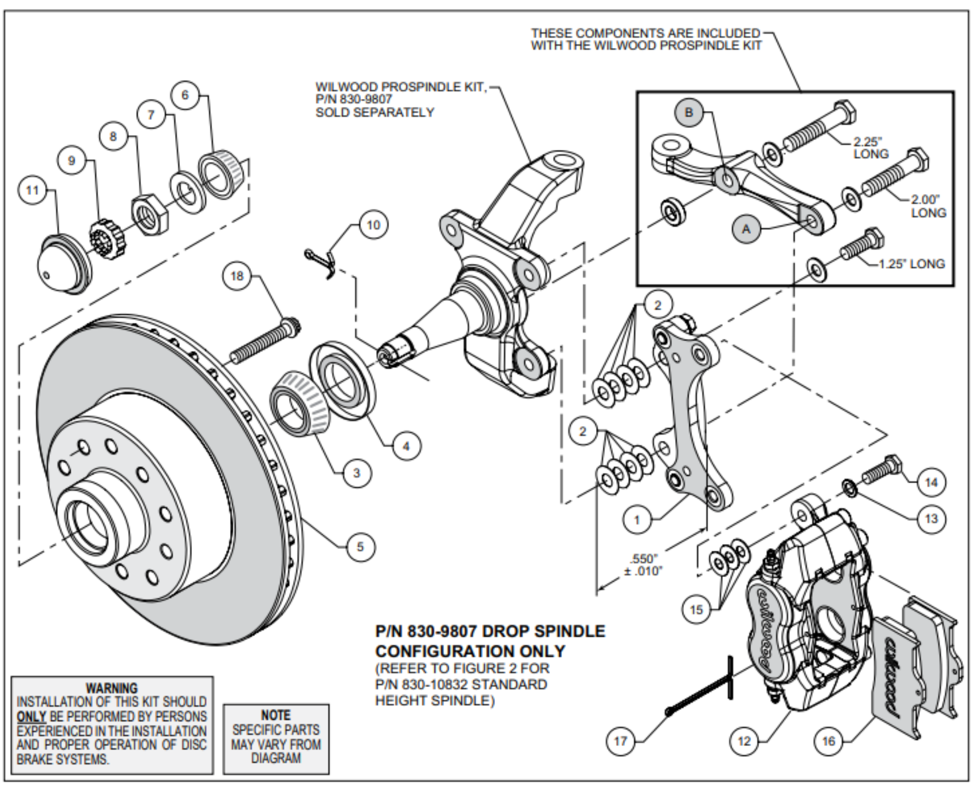

Figure 15 - Hub and Brake Assembly Shown as Mounted on Spindle.

The brake disc has a diameter of 11” and is compatible with wheels 15” and over. The hub assembly allows you to configure the hub to two different 5 hub stud patterns, 5 x 4.5” and 5 x 4.75”. The selected wheel has a 5 x 4.5” stud pattern.

Figure 16 - 15" Wheel, and Assembled Hub and Brake Kit.

The 15” wheel (right) is to be mounted to the fully assembled wheel hub and brake (left). The presented brake system’s hydraulic lines and master cylinders have not been selected however compatible kits are recommended on the linked product pages, this is to be left up to the team. The selected brake kit satisfies Shell competition requirements of requiring disc brakes on all wheels of the vehicle, ensuring the safety and eligibility of the design for competition.

8.0 Design Analysis

After creating the CAD model for the system and ensuring that it was able to function correctly and follow all of the rules set out the team then had to conduct analyses on the design to ensure it will not fail at competition. This was done through FEA and fatigue analyses of the portions of the design that experience the most force. The purchased were not thoroughly analyzed as they have all been designed to work on road going cars which are multiple times heavier, and travel faster than this vehicle.

FEA analysis was conducted on the side support of the steering system, as this part is subject to the highest loading in the system. ANSYS workbench was used to conduct the FEA analysis, yielding plots and maximum values for the Von-Mises stress and deformation experienced by the part under loading. The part was first loaded into ANSYS, and an automatic mesh generated using tri elements to ensure element size was consistent. Boundary conditions and forces could then be applied to the model. The part was fixed in all directions at each open face of the lower cylindrical tubing, as well as at the top open face of the rectangular tubing. Finally, two forces were applied to the faces in contact with the wheel spindle, as seen in Figure 17. Now with fully defined loads and boundary conditions applied to the meshed model, ANSYS solved for element Von-Mises stress and deflection. The material used for this part, Aluminum 6063-T6, has a yield strength of 172 MPa [14]. This value was used as an upper limit to ensure the maximum stress experienced by the side support was less than 172 MPa. A limit of 2 mm was used for the maximum deflection, again using this as the upper limit for deflection experienced by the part.

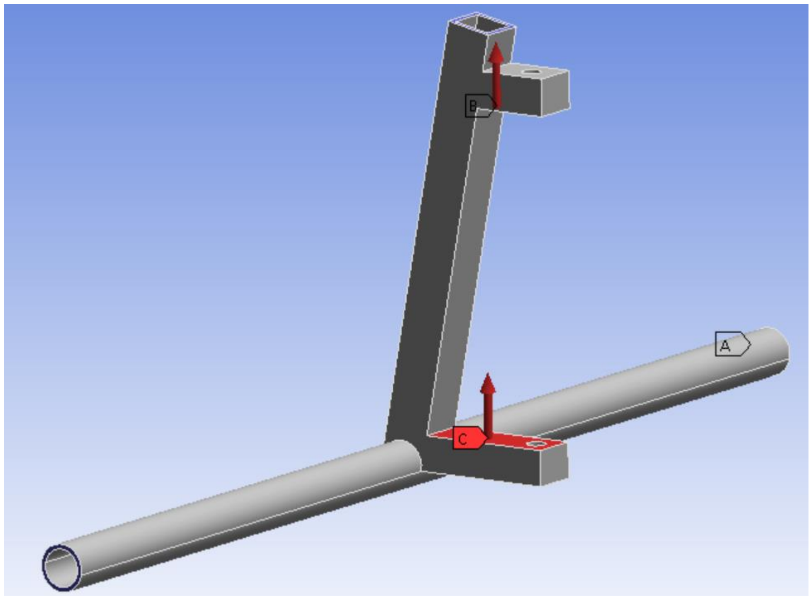

Figure 17 - ANSYS Screenshot of Where the Loading Occurs on the Spindle Mount for the Steering System Due to its Contact with the Wheel Spindle.

To account for both "best case" and "worst case" loading scenarios, two separate loading values were used. For both loading cases, the maximum stress experienced by the part was less than the yield strength of the material. Additionally, both cases yielded maximum deflections under the upper limit of 2 mm. This added certainty to the team's design and material selection, as failure will not occur even under the maximum loading calculated.

8.1 "Best Case" Loading Scenario

The "best case" loading scenario applied a force of 1464 N to the upper and lower support members. This loading scenario accounts for the maximum vehicle weight of 305 kg along with factors accounting for a 70/30 weight shift to the front and a 70/30 weight shift to one side dur to braking and turning of the vehicle. These weight shift estimates are quite exaggerated for the speeds the car is expected to run at, due to the endurance nature of the competition. This Normal force was used to solve for the reaction forces on the members and was applied as the 'best case' loading scenario.

The results from this analysis yielded a maximum stress of 29 MPa and a maximum deflection of 0.321 mm. Both values are well within the specified limits, ensuring failure will not occur under "best case" scenario loading.

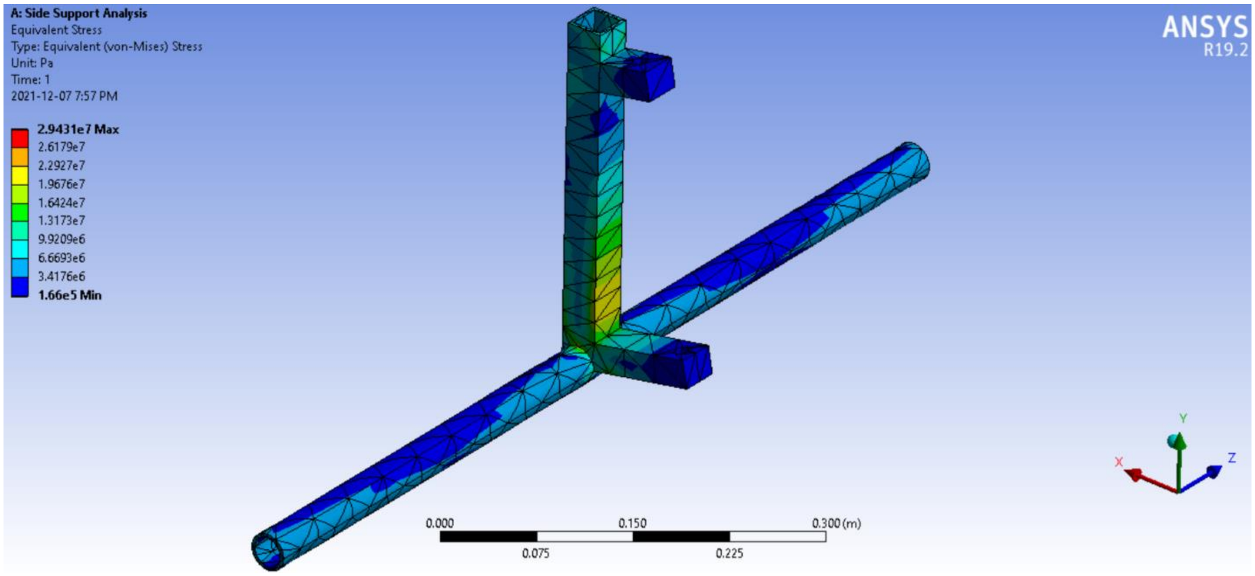

Figure 18 - ANSYS Screenshot of the Equivalent Stress Experienced in the Spindle Mount for the "Best Case" Loading Scenario.

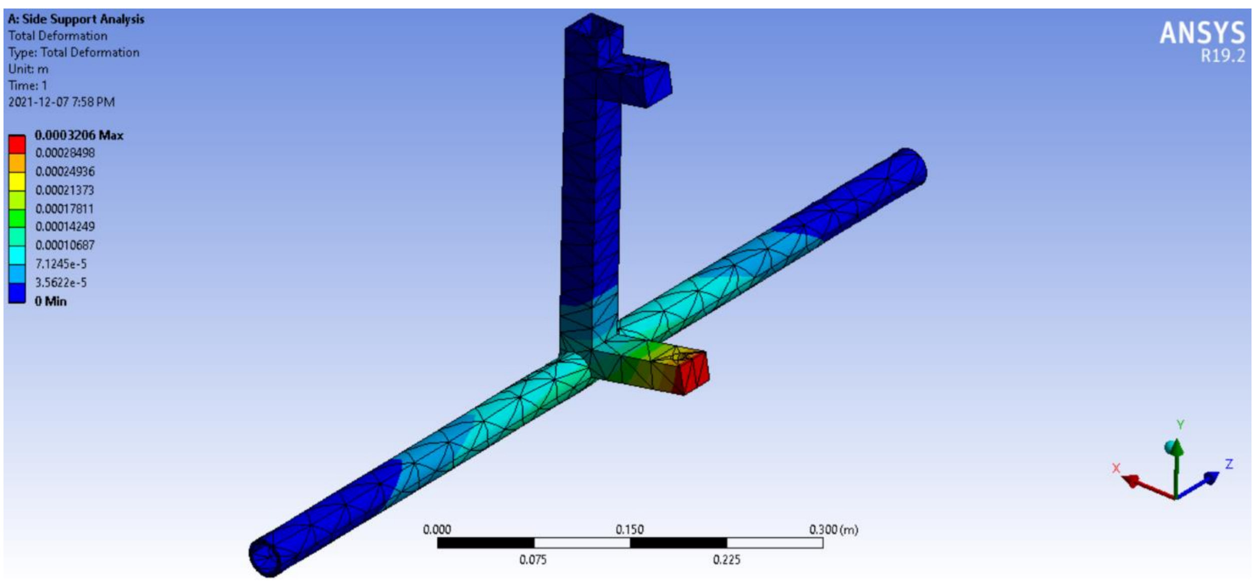

Figure 19 - ANSYS Screenshot of the Total Deformation Experienced in the Spindle Mount for the "Best Case" Loading Scenario.

8.2 "Worst Case" Loading Scenario

The "worst case" loading scenario applied a force of 6750 N to the upper and lower support members. This loading scenario was calculated by using the maximum vehicle weight of 305 kg, and applying factors to account for the following. The normal force consists of a 3g 'bump' factor to account for dynamic loading, a 0.7 factor for an assumed 70/30 weight shift to the front of the vehicle during braking, and another 0.7 factor for the assumed 70/30 weight shift to one side during turning. A 0.5g turning force is applied inwards on the wheel as well. The resulting reaction forces along with a 1.5 safety factor to account for welds in the structure, results in the calculated worst loading case of 6750 N.

The results from this analysis yielded a maximum stress of 136 MPa and a maximum deflection of 1.48 mm. As with the previous case discussed, the "worst case" loading scenario is within the limits of 172 MPa for stress and 2 mm for deflection. The team can now confidently deduce that the side support member will not fail under static and dynamic loading throughout the duration of the race.

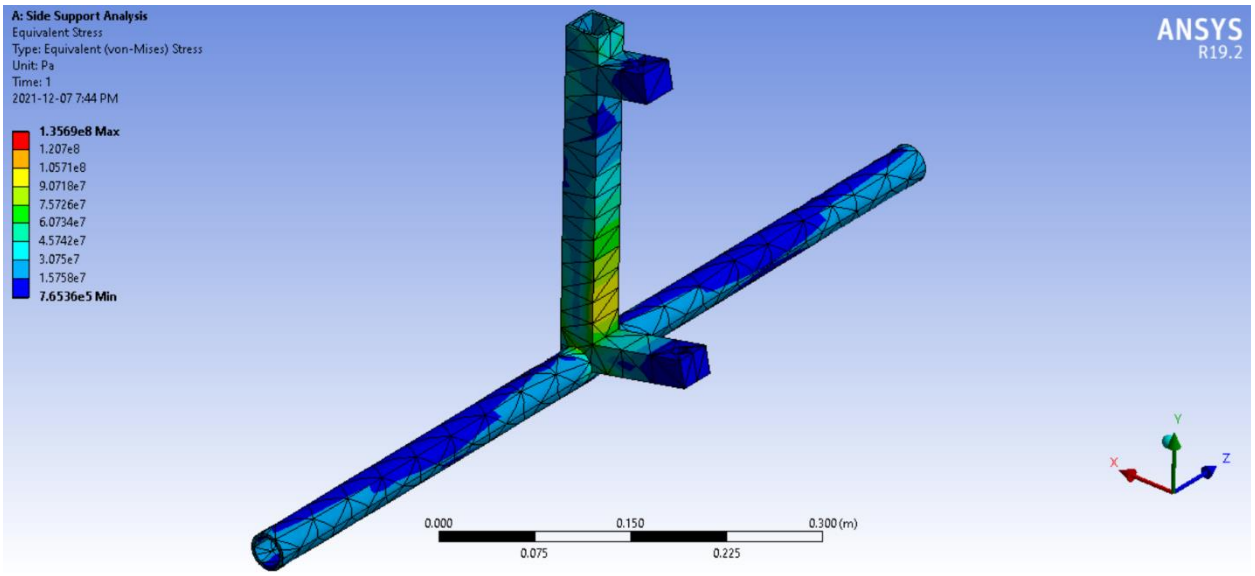

Figure 20 - ANSYS Screenshot of the Equivalent Stress Experienced in the Spindle Mount for the "Worst Case" Loading Scenario.

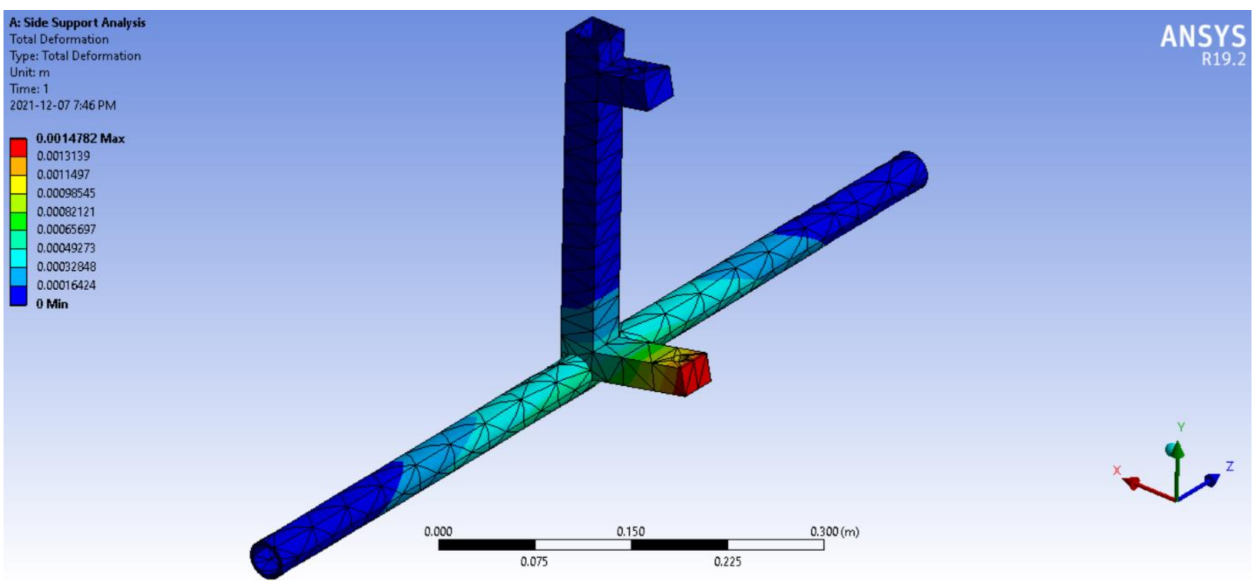

Figure 21 - ANSYS Screenshot of the Total Deformation Experienced in the Spindle Mount for the "Worst Case" Loading Scenario.

8.3 Seat Support

FEA analysis was also conducted on the seat support member to ensure failure does not occur under loading. The same process as with the spindle support analysis was used, fixing the member at each open end and applying a force of 2497 N on the top face. As this member is much longer than the side support part, an upper deflection limit of 2.5 mm was used. The results from this analysis yielded a maximum stress value of 61.9 MPa and a maximum deflection of 2.02 mm, both of which are below the limits of maximum stress (172 MPa) and deflection.

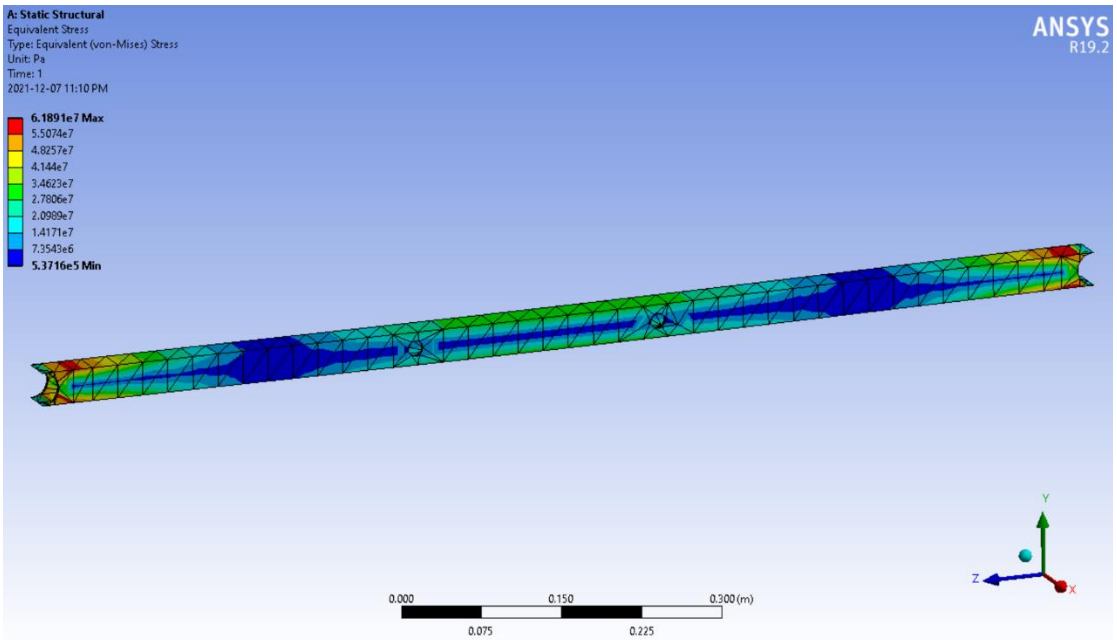

Figure 22 - ANSYS Screenshot of the Equivalent Stress Experienced in the Seat's Support Member.

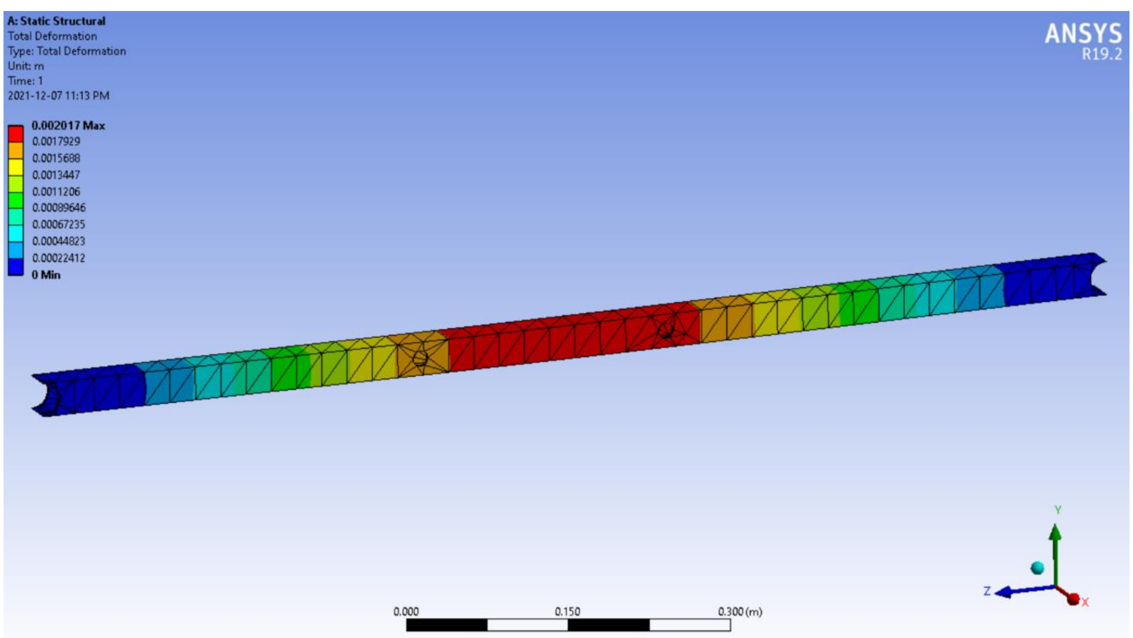

Figure 23 - ANSYS Screenshot of the Total Deformation Experienced in the Seat's Support Member.

8.4 Fatigue Analysis

Figure 24 depicts the S-N curve for 6063-T6 aluminum which is what is used for the spindle mount analyzed in the 8.1 “Best Case” Loading Scenario and 8.2 “Worst Case” Loading Scenario. The lines drawn onto the figure represent the “worst case” loading scenario, and as can be seen the system would be able to withstand approximately 600000 cycles of this loading. This number of cycles should be sufficient for the 10-12 expected hours of use of the vehicle under the worst conditions which this vehicle is never expected to actually experience. When analyzing the forces on the spindle mounts for the best-case scenario which looks exclusively at the vehicle when braking and turning simultaneously is well below the endurance limit of the material and cannot be plotted on this S-N curve because it is too small. As such the vehicle is expected to be able to last through the entire competition.

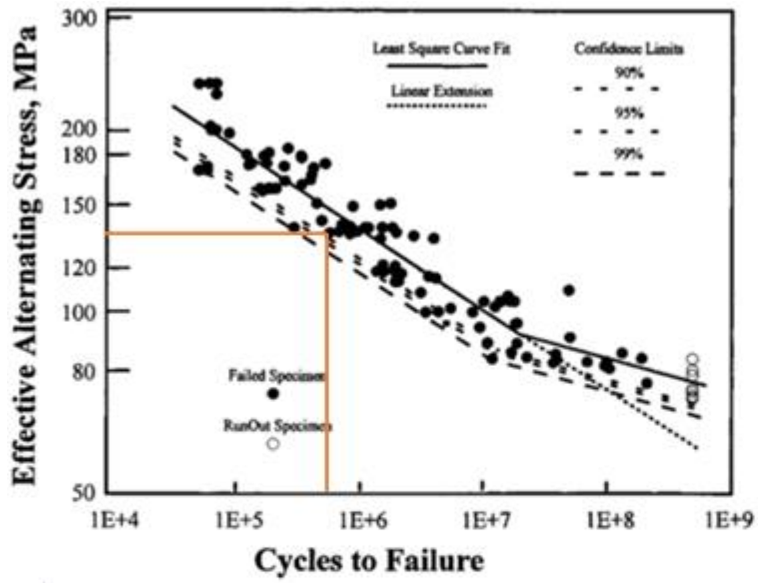

Figure 24 – Fatigue of 6063-T6 Aluminum [15].

9.0 Economic Analysis

The tables below display the estimated cost breakdown for all parts and materials that are in the final design of the suspension and steering systems for the vehicle. The total cost of this design is $3905.70 which is over double the upper bound of the budget. This price has been discussed with the client and has been accepted due to the purchase of materials that are out of scope or were thought to be out of scope by the client, but are still necessary to the function of the vehicle.

Table 8 displays the estimated cost breakdown for the raw materials that will be required in the final design. These materials will need to be processed in the McLaughlin Hall Machine Shop to match the parts that have been designed. The majority of these parts require minor amounts of processed such as just being cut to length, and some must be welded in place. The total cost has been adjusted to reflect the expected cost of use for the Machine Shop at $40 per hour. Engineering drawings for all parts that require have been provided in the Assembly Instructions.

Table 8 – Economic Analysis of the Raw Materials Required to Manufacture the Final Design.

Raw Materials				
Material	Supplier	Quantity	Cost Per	Total Cost
Tube Aluminum 6061 - I.D. 1.049", O.D. 1.33"	McMaster-Carr [16]	2 - 6'	52.83	125.66
Tube Aluminum 6063 - I.D. 1", O.D. 1-1/4"	McMaster-Carr [16]	1 - 8'	86.62	106.62
Square Tube Aluminum 6061 - I.D. 1", O.D. 1-1/4"	McMaster-Carr [16]	2 - 6' 1 - 3'	58.88 34.15	171.91
Square Tube Aluminum 6063 I.D. 1", O.D. 1-1/4"	McMaster-Carr [16]	2 - 6'	39.33	98.66
Aluminum 6063 Billet - 1.25" x 1"	OnlineMetals [17]	1 - 24"	24.71	64.71
6061 Aluminum Sheet - 1/4" x 4"	McMaster-Carr [16]	1 - 24"	37.73	57.73
			Total	**625.29**

Table 9 displays the cost breakdown for the steering system of the vehicle, focusing on the parts that convert rotational motion into linear motion. The only parts that will need to be processed in the Mclaughlin Hall Machine Shop are the steering shafts which must be cut to size and welded to the universal joints as described in the Assembly Instructions. The total cost of this section of the final design is $988.77; this cost has been minimized through cost analyses of sourcing these parts from various manufacturers.

Table 9 – Economic Analysis of the Parts Turn Rotational Motion into Linear Motion and Transfer that Motion.

Steering System				
Part	Supplier	Quantity	Cost Per	Total Cost
5/8 in. STEERING SHAFT KIT	Chassis Shop [18]	1	248.18	268.18
STILETTO RACK N PINION	Chassis Shop [18]	1	415.78	415.78
3/4 in. DIA TIE ROD KIT	Chassis Shop [18]	1	71.63	71.63
5/8" Universal Joints	Chassis Shop [18]	2	80.99	161.98
Steering Wheel	Kart Parts Depot [19]	1	57.38	57.38
M8 Steel Hex Nut (100 Pack)	McMaster-Carr [16]	1	6.14	6.14
M8 Steel Hex Screw (25 Pack)	McMaster-Carr [16]	1	7.68	7.68
			Total	**988.77**

Table 10 below displays the cost break down for the end effector of the system, this includes the spindle, the parts required to mount it, and the parts that mount on it. These parts will require no processing by the McLaughlin Machine Shop and will cost a total of $1804.65. This is a high price, but this is the best option available that meets all design requirements, and competition rules.

Table 10 – Economic Analysis of the End Effector of the Steering System.

Spindle and Parts Mounted on the Spindle				
Part	Supplier	Quantity	Cost Per	Total Cost
Wilwood ProSpindle 2" Drop	Wilwood [20]	2	279.51	559.02
Black Phosphate Steel Bolt	McMaster-Carr [16]	1	14.09	14.09
Steel Flange Nut	McMaster-Carr [16]	1	10.75	10.75
Dorman Spare Wheel and Tire	Summit Racing [21]	2	184.49	368.98
Wilwood Classic Series Dynamite Front Brake Kit	Wilwood [20]	1	770.27	770.27
Lug Nuts (20 Pack)	Amazon [22]	1	14.57	14.57
Ball Joint Adapter Tapered Bushings	Keyser Manufacturing [23]	2	6.49	12.98
M12 Black Phosphate Steel Bolt (10 Pack)	McMaster-Carr [16]	1	14.09	14.09
M12 Black Phosphate Steel Flange Nut (10 Pack)	McMaster-Carr [16]	1	10.75	10.75
M12 Washer	McMaster-Carr [16]	2	5.81	11.62
Rubber Dampener (Modified Hockey Puck)	Canadian Tire [24]	2	2.29	4.58
Red Loctite 271	Amazon [22]	1	12.95	12.95
			Total	**1804.65**

Table 11 Displays the cost of the remaining parts which did not fall into any other categories. The CARBONNect parts are required to integrate the designed system with the previously designed chassis and the suspension seat was the lowest cost option that will adequately dissipate vibrations before they reach the driver.

Table 11 – Economic Analysis of the Remaining Parts of the Final Design.

Other				
Part	Supplier	Quantity	Cost Per	Total Cost
Premier Suspension Seat	PRP Seats [25]	1	399.99	399.99
CARBONNect Main Block - Round - 1.0"	Rockwest Composites [26]	6	11.50	69.00
CARBONNect Adapter Kit - Round - 1.0"	Rockwest Composites [26]	2	9.00	18.00
			Total	**486.99**

10.0 Design Evaluation

To evaluate the final design the team has measured the final design against the original functional specifications defined in Table 2, Table 3, and Table 4. Table 12 below displays the functional requirements, the original target values, and the evaluation of the original design against those target values.

From this evaluation the final design has been determined to be a success. The system did not meet targets in sections relating to the construction of the vehicle, but meet or beat target values in sections relating to the function and performance of the vehicle and met all applicable Shell Eco-Marathon rules displayed in Table 5. The function, performance, and compliance with the rules are the most important aspects of the design. The functional requirements relating to the construction of the vehicle were set as internal team goals for the design of this vehicle and existed to act as reminder to simplify the design for the Queen’s Supermileage Team which has not constructed a vehicle in over 2 years. The design not meeting these target values is undesirable however, these requirements did serve their purpose to remind the team to maximize simplicity of the design. As such the design will not be considered a failure despite not meeting these targets.

Table 12 – Evaluation of Final Design Against Functional Specifications.

Functional Requirement	Target Value	Evaluation
Cost	Target: $1500 Minimum Requirement: $1800	The economic analysis resulted in a cost of $3905.70. This value is over double the original, but due to cost outside the expected scope the client has agreed to adjust the budget.
Longevity	Target: 100+ hours Minimum Requirement: 30 hours NOTE: Active run time of vehicle.	Based upon the FEA analyses and fatigue analyses performed on the final design the vehicle is expected to run for at least 30 hours.
Ease of Operation	Target: 5 Minimum Requirement: 2 Based on subjective driver rating out of 5.	Can only be evaluated after assembly and testing.
Weight	Target: 35 kg Minimum Requirement: 45 kg	Most part kits do no provide weight specifications for their contents. The estimated total weight of the design is approximately 65 kg. This value is larger than the initial weight specification however, this includes the unexpected weights of the seat, braking system, and a chassis redesign. The systems weight has also been minimized and for lighter materials cost will increase exponentially.
Number of Parts	Target: 20 Minimum Requirement: N/A	There are 39 total unique parts not including small hardware such as nuts, bolts, washers, and cotter pins; this value also includes the number of parts in the various part kits. This is larger than the initial target value due to the design being more complex than originally thought. This is acceptable because the design cannot be made simpler from its current state without becoming less effective a solution.

Functional Requirement	Target Value	Evaluation
Number of Steps to Assemble	Target: 40 Minimum Requirement: N/A	There are a total of 65 unique steps required to assemble this final design. This is larger than the target, but is acceptable because the design cannot be made simpler without becoming less effective a solution.
Number of Tools Required	Target: 30 Minimum Requirement: N/A NOTE: Majority of tools and machinery required must be available in the McLaughlin Hall shop.	This design requires 19 unique tools. This does not include tools used in the fabrication shop when processing the raw materials, and tool kits such as a socket kit are counted as 1 unique tool.
Time to Assemble	Target: 20 hours Minimum Requirement: N/A NOTE: Must be assembled for testing before the competition at the end of the ‘21-’22 school year.	Cannot be evaluated before the design is constructed. Due to the number of unique parts and steps required to assemble the design being higher than the target value, this is also expected to be larger than the target value of 20 hours. This will still be acceptable as the design will not take an unreasonable amount of time to assemble.
Positive Interactions with Other Systems	Target: 3 Minimum Requirement: 0	The steering and suspension systems positively interact with each other however, the chassis had to be redesigned to accommodate these systems which is a negative interaction. The final score for this functional requirement is 0, which is acceptable.
System fail-safes	Must be able to keep the driver safe in the event of a system failure.	The driver will be separated from the majority of the design through the bulkhead. The seat has now been designed to be fixed directly to the chassis opposed to simply secure with plywood. The upper universal joint will also act as an anti push back on the steering shaft support beam, securing the steering shaft. These will both be safer in the event of a vehicle failure such as a crash or rollover.

Functional Requirement	Target Value	Evaluation
Suspension Specific		
Loading capabilities	Target: 400 kg Minimum Requirement: 350 kg Note: This is full vehicle weight; it is assumed there will be even weight distribution between the front and rear	From the FEA analysis the front spindle mounts will be able to withstand the forces it will experience. The worst case FEA analysis effectively puts 1.5 time the vehicle weight onto a single mount, and it does not reach failure.
Max Obstacle Height	Target: 3.5 cm Minimum Requirement: 2.5 cm	The worst case FEA analysis used the assumption of a 3g force bump which is larger than the force that would be experience from this sized bump. The tire choice will also be able to overcome this bump easily.
Steering Specific		
System Friction	Target: 40 N Minimum Requirement: 60 N NOTE: Force measure at outer diameter of steering wheel.	This could not be effectively modelled through the complex loading the steering system will experience. However, this rack and pinion chosen for this system is designed for a full-sized vehicle, and so the mechanical advantage provided should result in a reasonable amount of force being required to turn the vehicle.
Ergonomics	Target: 5 Minimum Requirement: 2 Based on subjective driver rating out of 5.	Can only be evaluated after assembly and testing.

11.0 Conclusion and Recommendations

The Queen's Supermileage Team needs their vehicles front suspension system and the steering system to be designed for the 2021 – 2022 Shell Eco-Marathon Competition. After an analysis of the team's needs various ideas for design solutions for each of the suspension and steering systems were analyzed and the best options were chosen. For the suspension system the design is centered around a suspension seat while the steering system was determined to be a rack and pinion design. The suspension seat to be purchased is intended to dampen the vibrations as they travel to the driver of the vehicle. This design is affordable, reliable, and greatly decreases the complexity of the steering system as the tie rods do not need to adjust to constantly changing suspension. Two aluminum beams are to be added to the bottom of the chassis to improve rigidity of the vehicle, add more support for the floor and seat, and mount the seat. In addition to the suspension seat design, rubber vibration dampening pucks are to be added to the top of each spindle in the steering system to dampen some of the vibrations to improve the longevity of the vehicle. The chosen rack and pinion design for the steering system was found to be the simplest and most cost-effective solution for the vehicle's short-term nature. It features a center mounted rack and pinion, steering column, spindles, and additional custom support members to be integrated into the chassis to support and mount all the components to. The spindles are designed to mesh with a particular braking system so this was also included in the final design despite being outside the scope. To ensure all the components are adequate in dealing with the loading, the purchased parts were selected accordingly, while the custom parts were analyzed in ANSYS. The total cost of the project is estimated to be $3905.70, greater than the given $1500 budget, but as the design went outside of the original scope, the client agreed that this cost was acceptable. Detailed assembly instructions and parts lists documents were also created for ease of assembly when building the vehicle next semester.

Moving forwards with this project it is recommended that a different chassis design be used. While this report includes added components to the chassis to improve its strength and rigidity, due to the nature of the small connectors, set screws, carbon fiber tubes, and minimal analysis done in the initial design, there is concern for the overall safety of the vehicle and potential risk of failure. If the chassis design is decided to be used, it is recommended that the entire bottom layer of members in the chassis be made from aluminum.

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Appendix

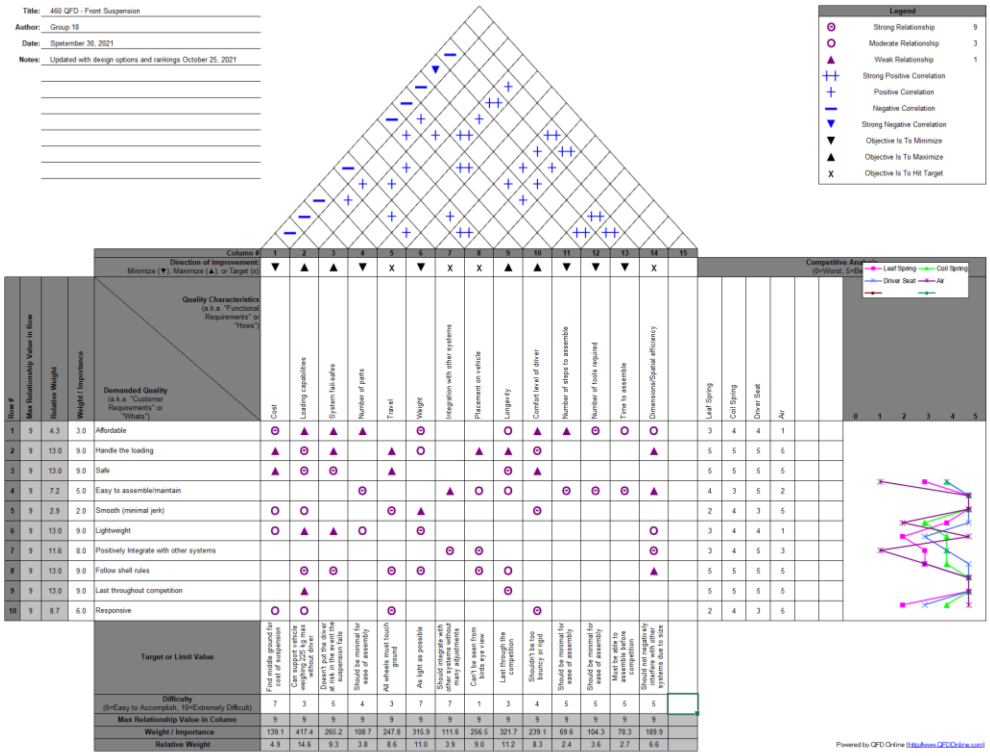

Figure 25 - Front Suspension Quality Function Deployment (QFD).

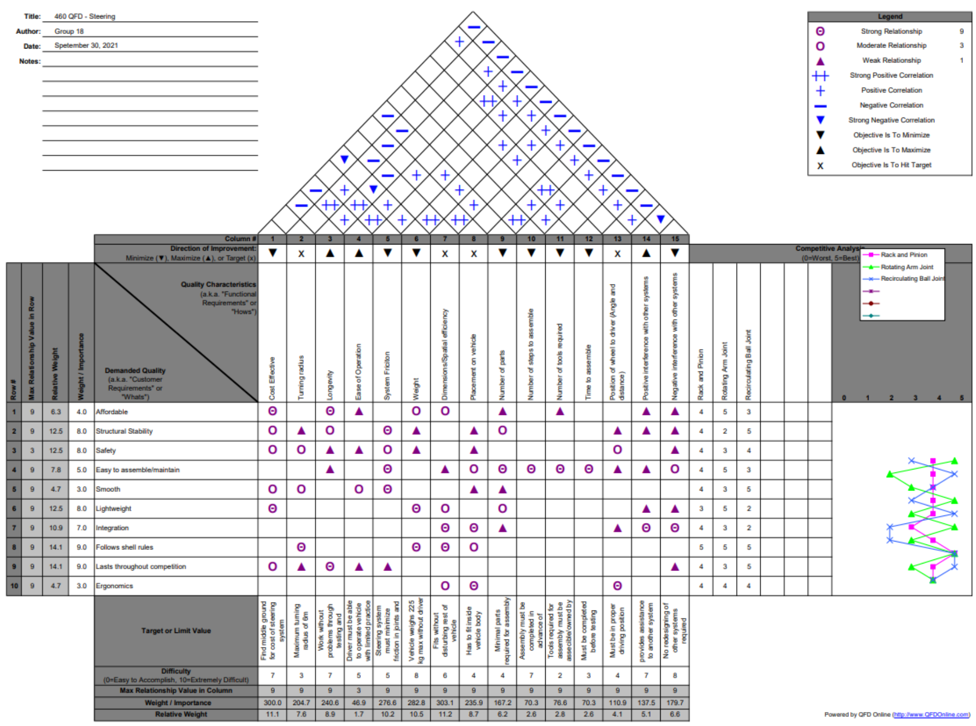

Figure 26 – Steering Quality Function Deployment (QFD).