MEMO

To: Dr. John Tester

From: Moneer Al-Jawad, Jericho Alves, Daniel Chief, Benjamin Kurtz

Date: December 13, 2013

Subject: Shell Eco-marathon Project Proposal

Dr. Tester, the following document contains the final designs for the chassis, fairing, braking systems, and steering system for the 2013-2014 Shell Eco-marathon senior design project. The estimated cost of a prototype, not including the engine, drivetrain, fuel systems, and electrical systems is $1,607. Construction of the final design is expected to occur at the start of January. Testing of the final design is expected to start at the beginning of March.

Shell Eco-marathon

By

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Team 14A

Project Proposal

Document

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Mechanical Engineering Design I – Fall 2013

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Nomenclature

a = Load to nearest support

A = frontal area

C_{rr} = dimensionless rolling resistance coefficient

C_D = Drag coefficient

d= diameter of the rigid wheel

δ_i = steering angle of the inner wheel

δ_o = steering angle of the outer wheel

δ_{max} = Maximum deflection

E = Elastic modulus

F_D = Drag force

F = Weight of driver and car

F_r = Rolling resistance force

F_f = friction force provided by the calipers

F_{cal} = force by one side of caliper onto the rotor

F_l = left hand lever force

F_{clamp}= clamping force

I = Moment of inertia

L = Length

l = distance between the front and rear axles (wheelbase).

l_r = distance between the car's center of gravity and the rear axle

μ_{bp} = coefficient of friction between the brake pad of the caliper and the rotor

N = dimensionless rolling resistance coefficient

R = Turning Radius

r = radius of the wheel

r_{eff} = radius between the center of the rotor and the center of the caliper

r_{force}= force radius

r_{arm} = lever arm

ρ = Density

T_r = parking torque

v = Velocity

W = distance between the steer axes of the steering wheel (track).

w = weight

x_1= Point of maximum deflection

z = sink depth

Abstract:

Designing a full structured vehicle requires a lot of engineering design concepts. These concepts must be applied properly to ensure that the vehicle will be built properly and efficiently. Shell requires student to design, build, and operate their vehicles under certain rules and regulations such as low fuel usage. Team 14 is designing a vehicle to compete in the Shell Eco-marathon competition and this vehicle will fulfill all these rules and regulations. The team has limited budget of $1500 provided from Northern Arizona University. The team is trying to increase the budget by soliciting tax deductible donation from local or regional suppliers.

This report will provide the information needed to accomplish the final design of the vehicle. Our team (14A) is responsible for the Chassis/Fairing, Steering, Braking, and Safety equipment cost. These parts listed will be the main components of the vehicles structure.

First, concept generation and selection will describe the choices that the team decided to go with for each component. Also, it will discuss the advantages of the selected designs and will illustrate why the design was chosen.

Then, deep engineering analysis will be providing analyze to each component. It will, also, be showing the equations needed to calculate drag force, deflection of chassis, turning radius, rolling resistance, torque, and force required to hold the vehicle on a 20% grade slope.

Later, an engineering economics and parts costs will be available to show the total amount needed to complete the shell eco-marathon vehicle. These costs will sum together to provide a total cost and the total will be compared to the team's budget.

Finally, a table will be presenting the safety equipment required on every team involved in shell competition. The table will also include the name of safety parts required, supplier, and their costs. These costs are counted toward the overall budget.

Chapter 1: Introduction

In engineering fields, the mechanical engineers involved in many engineering aspects such as designs, machine developments, manufacturing systems, and solution of environmental problems. One of the great characteristics that mechanical engineers have is their creativity and their long breadth of knowledge, therefore a lot of elements relies on mechanical engineers. The main client for this project is shell, because they are adopting this competition every year to identify the know ideas provided by competitors to reduce gas emissions.

1.1 Problem Definition

One of the main issues our society is facing is the constant increase in the temperature of the earth's atmosphere, also known as global warming. A rise in the temperature in the atmosphere can cause ice to melt around the Earth's poles, a rise in sea level, and an increase in rainfall and snowfall worldwide. This phenomenon is mainly caused by greenhouse gases produced by the burning of fossil fuels. According to the United States Environmental Protection Agency, 28% of greenhouse gas emissions come from burning fossil fuels in transportation. Oil refined as gasoline to fuel cars, trucks, and other highway vehicles is the main fossil fuel used in transportation.

The Shell Eco-marathon competition is designed for students to find innovative solutions in transportation to help reduce the release of greenhouse gas emissions in vehicles. This includes finding alternative energy sources as well as optimizing the energy sources we have today.

Our goal is to design, build, and compete with a car prototype that maximizes fuel efficiency of an internal combustion engine to compete in the Shell Eco-marathon Americas competition in Houston, TX. The design of the chassis and steering systems will minimize weight, maximize aerodynamics, and follow all regulations of the competition under a low budget.

Our focus is on the design of the chassis and steering as well as covering all safety requirements of the driver and the car.

1.2 Objectives

The objectives for the Shell Eco-marathon car are shown in Table 1.1. Table 1.1 also shows the benchmark of how Team 14A is going to test each objective and its corresponding unit of measurement.

Table 1.1: Objectives for Eco-marathon car

Objective	Benchmark	Unit of Measurement
Lightweight	Chassis Weight	Kilograms
Rigid	Deflection Under Load	Centimeters
Aerodynamic	Drag	Newtons
Low Cost	Cost	US Dollar

1.3 Chassis / Fairing Constraints

The following section will outline some specific needs and constraints relating to the Eco-marathon vehicle chassis and fairing. These constraints were derived from the Shell rulebook Chapter 1.

Dimensional Constraints (Article 39) [1]

- Length: 350cm Maximum
- Width: 130cm Maximum
- Height: 100cm Maximum
- Track Width: 50cm Minimum
- Wheelbase: 100cm Minimum
- Height/Width Ratio: 1.25 Maximum

Design Constraints

- The chassis must incorporate a roll bar that extends 5cm above the drivers head, and past the width of the drivers shoulders with the driver in the standard driving position with the seatbelts fastened. The roll bar must be able to withstand a 700N load without deflecting.
- The vehicle fairing must cover all drivetrain associated parts.
- The cover around the engine must be easily removable to facilitate inspection access
- Vehicle with wheels mounted inside the faring must have a bulkhead that separates the wheels from the driver.
- The vehicle must have a full floor that will prevent the driver from any contact with the ground at any point during normal operation.

● Vehicle windows must be made from a material such that in the event of an impact, they do not break into smaller shards.

● The vehicle fairing must not impede driver visibility directly ahead of the vehicle or 90 degrees to either side of the vehicle's longitudinal access.

● Any active aerodynamic apparatus are specifically prohibited [2].

● Vehicle must be designed to allow the driver to vacate the vehicle in less than 10 seconds, starting from a fully harnessed position.

● The driver access portion of closed body vehicles must be easily accessible from both inside and outside of the vehicle and must be possible to open without tools. Exterior latches must be clearly marked with red arrows.

1.4 Steering Constraints

Tires and Wheels

- All types of tires and wheels are allowed.
- Rims must be compatible with tires.
- Wheels inside the vehicle body needs to be isolated from the driver by a bulkhead.
- Wheels are required not to come in contact with any other parts of the vehicle.

Axles

- Wheel axle should be designed for cantilever loads.

Turning Radius

- Front wheel or rear wheel steering is allowed.
- If rear wheel steering is used, the driver should be able to locate the straight ahead position.
- The turning radius must be sufficient to safely make turns on the track.
- If turning radius is insufficient the organizers may recommend to drive the slalom course, which has a turning radius of 8 m.
- Indirect electronic steering system is permitted, providing they are operated by a steering wheel or something similar.

1.5 Braking Constraints

- The systems must be independent
- one system on front wheel(s) and the other on rear wheel(s)
- If there is more than one wheel on the front or rear then both wheels have to be braked unless there is an axle tying them together that can be braked
- Systems must be able to be engaged simultaneously

1.6 Summary

Constraints were given to teams competing in the eco-marathon, through the shell eco-marathon official rules 2014. The NAU eco-marathon team used these constraints to design the chassis, fairing, steering and braking.

Chapter 2: Concept Generation and Selection

2.1 Introduction

The concept generation and selection for chassis, fairing, steering and braking is included in this section. Three possible design is selected. The final concept decision is chosen by using a matrix.

2.2 Chassis/Fairing Concept Generation

Design Considerations

Development of the chassis and fairing or monocoque will be determined by what resources we can secure in the near future. As a team, the initial budget and resources afforded to us are limiting and would likely direct us towards creating a thermoplastic fairing supported by an aluminum frame. If additional sponsors become available, we can make composite structures and move towards a monocoque chassis which is lower in overall weight and also produces less drag.

Preferred Construction Method

The ideal chassis construction is a composite monocoque which encloses the wheels completely. The shell is made with two separate plugs. The molds increase the complexity of construction. The main benefit of a composite monocoque, as stated previously, is an extremely rigid yet lightweight chassis. Enclosing the wheels restricts the turning radius, so it is crucial to do extensive analysis prior to construction to ensure suitable maneuverability.

Possible Design Alternatives

The first design alternative consists of a tube frame chassis preferably constructed out of aluminum. The frame would run the length of the vehicle and support all suspension and driveline components as well as the roll bar. This design is the least preferable method as it weighs the most. The main benefit of this design is that we can manufacture the entire frame in house with the aid of NAU staff. The fairing can be made from a single plug and mold. The fairing can be a streamlined half body or possibly made from flat flexible sheeting. Again this design is a compromise in order to maintain a short build time with little to no resources outside of the engineering department at NAU.

The second design alternative is a monocoque chassis with unenclosed wheels. This design is a simple yet agile design, which could easily integrate subsystem design changes without redesigning the chassis itself. Construction of an unenclosed wheel monocoque chassis is accomplished by making a monocoque chassis similar to the method listed above, but keeping the wheels outside of the shell. In the instance that hubs, brake systems, or steering components need to be redesigned to increase performance or shed weight, they can be changed with minimal impact to the shell. The construction would again require resources outside of NAU, but is much less complicated than creating a chassis with wheel fairings.

2.3 Steering Concept Generation

2.3.1. Rack and Pinion Steering

Rack and pinion steering is the most common type of steering [3]. Rack and pinion systems are enclosed in a metal tube with the ends of the rack protruding the tube. A tie rod is attached at the end of the system and is connected to the steering arm on the spindle. The steering wheel turns the pinion gear, the pinion moves the rack, converting rotational motion to linear motion. This motion applies force to the tie rod and steering arm. The steering arm is attached to the wheel, which causes the tires to turn. Rack and pinion steering is most common on the front wheel drive vehicle.

The advantages of the rack and pinion are: it has a large degree of feedback and direct steering feel, it has fewer moving parts, the driver has more control, the rack and pinion are smaller and takes up less space. The disadvantages of the rack and pinion: it is not adjustable when it wears, the simple construction causes the transfer of noise and vibration to the driver and passengers, off-roading wears the linkage.

2.3.2. Worm and Roller Steering

Worm and roller steering consists of a roller which is meshed with a worm gear enclosed in a box [4]. The roller is shaped like an hourglass so the roller will not disengage when in motion. The worm is located at the end of the steering shaft. An arm, called the Pitman arm, is attached to the roller. The Pitman arm is connected to the steering mechanism which turns the wheels.

Worm and roller steering works when the steering wheel turns the worm, the roller turns with it, forcing the sector and Pitman arm to rotate.

The advantages of the worm and roller steering are: simple in construction, it is easy to build and maintain, there is little effort in turning the steering wheel. The disadvantages of the worm and roller steering: there is a lot of friction between the worm and roller.

Decision Considerations

Cost is defined as the amount of U.S. dollars it will take to purchase or build the entire steering system. Cost is important because we have a budget to maintain. The relative weight for cost depending on sponsors and donations of materials is 0.30.

Space is defined as the amount of area the steering system occupies. In order to reduce drag we will like the vehicle compact without bulky components so the relative weight for space is 0.1.

Efficiency is defined as the amount of feedback and direct steering feel. The ease of making turns around corners while driving the course. The relative weight is 0.45 this is due to the safety of the driver.

Weight is defined as the amount of force an object has due to gravity. The overall weight of the steering system is not as important as efficiency so the relative weight is 0.15.

The simple arm design was chosen based on the decision matrix in Table 2.1. Cost will not be outrageous. The team will be using last year's steering parts. Parts damaged or worn out will be ordered. Modification from the Pitman arm reduces the space taken up by the gearbox. The eco-marathon vehicle will not being going at high rates of speed. Driver feedback and direct steering is important to the driver for safety. This is the reason why the efficiency is significant. Overall weight of the vehicle is vital to the competition. The lighter the vehicle the less torque is needed to get the vehicle moving. Raw score is calculated by adding cost, space, efficiency, and weight all together. Using Simple arm as an example: Weight Total=.3*8+.1*5+.45*6+.15*3=22

Table 2.1: Steering Concepts Decision Matrix

	Relative Weight	Simple Arm	Worm & Roller	Rack and Pinion
Cost	0.30	8	5	7
Space	0.10	5	3	3
Efficiency	0.45	6	4	2
Weight	0.15	3	2	2
Raw Score		22	14	14
Weighted Total		**6.05**	**3.9**	**3.9**

2.4 Braking Concepts

The vehicle needs to be able to not only maneuver very well through the course, but it also needs to be able to immediately because sometimes it is not reasonable to try to maneuver around an obstacle. There are many braking systems available out there, but the three that were seriously considered for this project are disk brakes, caliper brakes, and drum brakes.

The disk brakes for a bicycle are very similar to those for the average sedan. The main difference being that they are much smaller given that they don't need to be able to stop over a ton of steel going 75 mph, but rather only a few hundred pounds of force going 40mph. There are specialty bicycle disk brakes that are capable of providing stopping force for bicycles going those speeds but that is not a necessary for this project. The basic concept is that a caliper is pressed onto a rotor that is attached to the wheel, therefore having the same angular velocity, such that the kinetic energy of the wheel is changed to thermal energy. One large advantage to this kind of system is that it is not nearly as prone to getting debris in the system as it comes up from the road because the system is at a greater distance from the road than other systems. An example of this is system is shown in Figure 2.1.

Figure 2.1: Disc Brakes

The second evaluated system is the caliper braking system. This is generally the simplest kind of braking system to implement, it is also one of the cheapest. There are several varieties of this system, but the general concept is that there are brake pads attached to arms mounted near the rim of the tire. When the brake lever is squeezed the pads apply force to the rim of the wheel turning some of the kinetic energy of the system into thermal energy. This type of system is very easy to implement because many variations only need one mounting point near the tire and the cable to actuate the mechanism. An example of this type of system is shown in Figure 2.2.

Figure 2.2: Caliper Brakes

The third type of braking system evaluated for this project is the drum brake. These kind of brakes are often used on cruiser type bicycles where the rider pedals a short amount in the reverse direction engaging the brake. This kind of brake is not effective for extended duration braking because it does not have a very effective solution for getting rid of the heat created by braking. Drum brakes are generally the same type of system as in cars, however greatly scaled down due to the reduced force required. This type of brake is generally more difficult to service, however due to it being an an enclosed system it is more robust requiring service at longer intervals. An example of this type of brake is shown in Figure 2.3.

Figure 2.3: Drum Brakes

2.4.1. Decision Matrix

The decision matrix below Table 2.2 is rated on a modified scale of 1-10. The scale has 3 positions: 1, 5, and 10. The best being 10 and the worst being 1. The raw scores were multiplied by a weighting factor to get the final score for each potential braking concept.

The categories assessed in the decision matrix are the weight, reliability, cost, and simplicity of the system. The weight of the system is deemed important because it is necessary to have a system that keeps the weight down. A lightweight system will help in the pursuit of higher gas mileage as the less weight that is accelerated during the run of the course the less energy is required. A lighter weight also allows for more weight to be used other places while maintaining the same overall weight. The drum brake system is relatively a very heavy system because of the general size it takes to get the same amount of braking force out of the system. Both the caliper and disk systems are very light because there is a relatively small amount of material in both systems.

The reliability of the system deals with how long it is expected to run without issue. This goes both into how well it dissipates heat as well as how well it can be expected to not get clogged up in the course of normal operation. The disk brake system is generally more reliable than the others owing to the fact that it avoids the downfalls of the other two systems. Namely that it is farther removed from the driving surface so it doesn't get nearly as much debris in the system during normal operation, which is the major issue with caliper style brakes, and it also has an open design that is quite good at dissipating heat which is the downfall of drum style brakes.

The simplicity of the system is related to the amount of time, both design and implementation, that it takes to get the system working. The disk and caliper systems are about the same simplicity because all they need is a mounting point and the actuation system, whether that be cable or hydraulics. The disk braking system is more difficult to implement due to the fact that it generally goes inside the hub of the wheel and requires a stationary mounting point on the frame.

The cost of the systems if the most straightforward part of the system to evaluate. The cost is very important to keep down due to the fact that there are limited funds available to the team for the project. If money was not an issue the team would go with the most effective brakes available, but as it is the team must choose the most effective brakes available for the money that is allotted for braking.

Table 2.2: Braking System Decision Matrix

	Relative Weight	**Disc**	**Caliper**	**Drum**
Weight	30%	10	10	1
Reliability	30%	10	1	1
Simplicity	10%	10	10	5
Cost	30%	5	10	5
Total	100%	**8.5**	**7.3**	**2.6**

The decision matrix spells out that the system to go with is the disk brakes. The caliper braking system comes in at a close second place so it is a potential option if disk brakes cannot work out.

2.5 Summary

The designs selected above were based off of criteria defined by the group. The criterion defined is different for each section. Each section consisted of three concepts and the best concept was chosen. A solid frame monocoque design is chosen for the fairing and chassis section because it is light.

In order to proceed with the design selection, our team needs to know our initial budget. Unfortunately, the budget for our team is still being worked out by SAE and outside companies. In response, the concepts selected for each of the designs are preliminary. Once we know closer estimate of the resources available for the eco-marathon project, we can continue to work out our designs.

Chapter 3: Engineering Analysis

3.1 Introduction

Engineering analysis of chassis, fairing, steering and braking are calculated using different equations. For the chassis drag for is considered. In steering, the Ackermann steering geometry is used. Braking force is calculated based on the eco-marathon rule book. The rules states that the vehicle and driver must be held in place at a 20 percent grade.

3.2 Chassis Analysis

The main focus when analyzing the aerodynamic performance of the vehicle fairing is the overall frontal area. The area is largely a function of driver positioning and visibility requirements. Both drivers that are going to be going to the competition are measured in a seated position to find the greatest angle they could be reclined to and maintain adequate visibility and driver comfort [5]. A vector diagram of the proposed driving position is then made and overall height requirements of the fairing are determined. This can be seen in Figure 3.1 below.

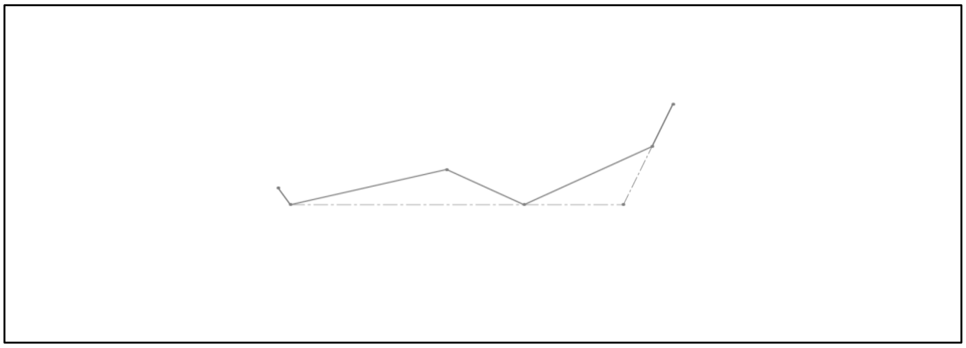

Figure 3.1: Driver Position Diagram

The frontal area is then calculated as a function of the seatback angle using a uniform width of .6 meters which allows for the width of the drivers shoulders and a high density foam side bolster. This is represented in Figure 3.2 below.

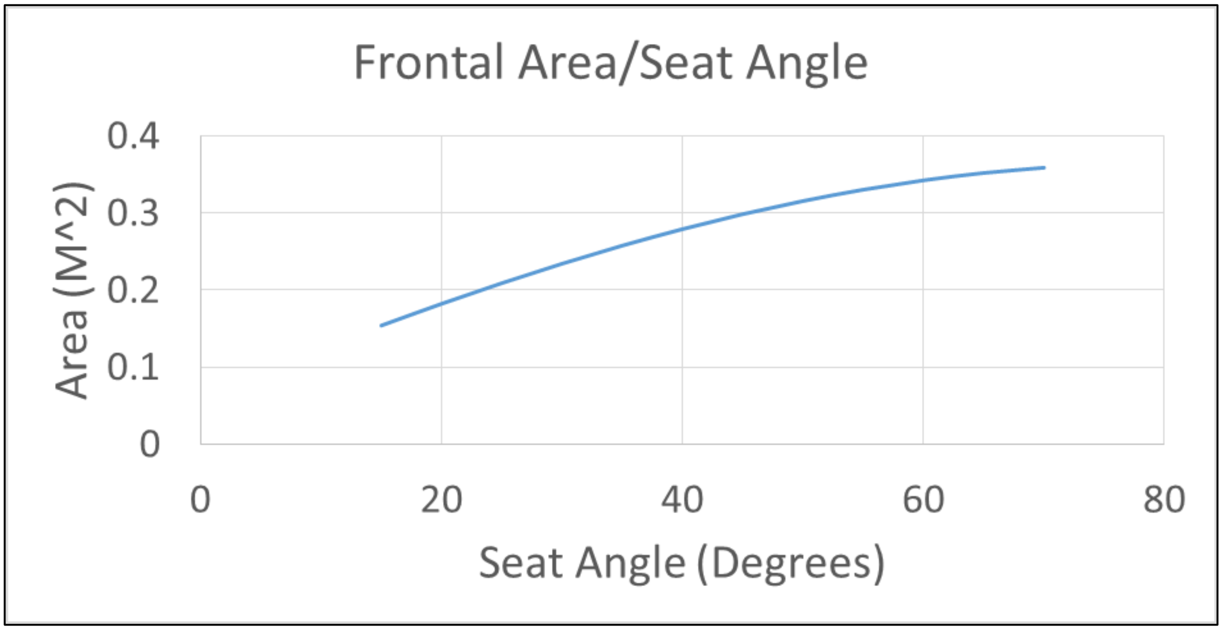

Figure 3.2: Frontal Area/Seat Angle

The drag force is calculated over a range of frontal areas in order to see the drag effects over the entire range of speeds the vehicle would see. The coefficient of drag (Cd) is initially set to 0.09 which is the standard for a streamlined half body. A plot of drag forces versus vehicle speed is shown in Figure 3.3.

Drag Force $$F_D = \frac{1}{2}\rho v^2 C_D A$$

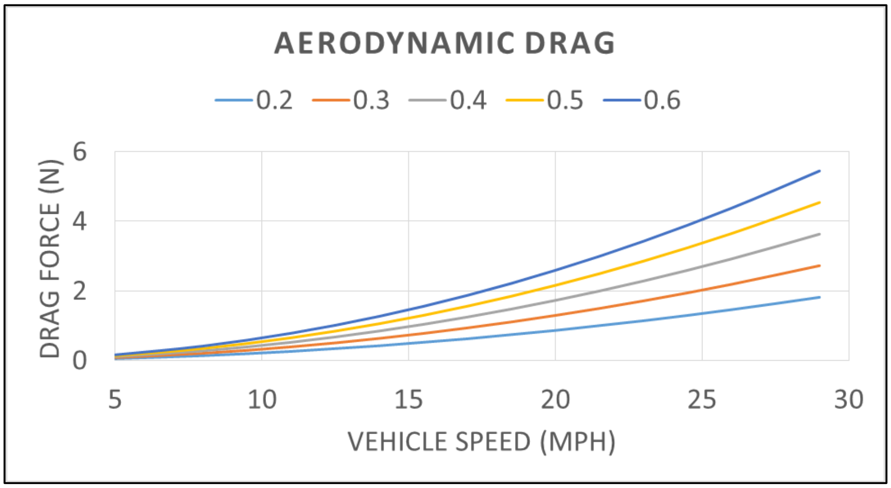

Figure 3.3: Force of Aerodynamic Drag

Additional fluid mechanics based considerations determine the overall shape. To maintain an ideal streamlined body the fairing tail section reduction should not exceed 22 degrees in the YZ or XZ plane to ensure flow separation does not occur. Flow separation causes turbulent vortices to form increasing the drag force acting on the body. The chassis floor should taper between 3-4 degrees towards the rear of the vehicle to reduce turbulence of the merging flow paths coming from above and below the vehicle [6].

3.2.1. Chassis Rigidity

Chassis rigidity is determined by taking a cross section of the shell at the center of mass including a 55kg driver seated in the standard position. The polar moment of inertia is taken at this point and used to determine overall chassis deflection and its location using the following equations.

Maximum Deflection
$$\delta_{max} = \frac{Fa(L^2 - a^2)^{3/2}}{9\sqrt{3}LEI}$$

Point of Maximum Deflection
$$x_1 = \sqrt{\frac{L^2 - a^2}{3}}$$

The cross section evaluated at point *a* is 0.6 meters from the rear wheel. Initial wheelbase dimensions are somewhat arbitrary as all components have not been finalized. The elastic modulus is determined from a mean value of multiple 3000 weaves from multiple carbon fiber manufacturers. Chassis Rigidity variables are listed in Table 3.1 and deflection values are listed in Table 3.2.

Table 3.1: Chassis Rigidity Values

Variable	Value
a (Load to nearest support)	.6 m
L (Wheelbase)	2.5 m
X (Point of maximum deflection)	1.484 m
E (Elastic Modulus)	141 GPa
I (Moment of Inertia)	.079 m^4

Table 3.2: Chassis Deflection Values

Load at a	Maximum Deflection at x
60	1.19 mm
90	1.78 mm
120	2.37 mm

3.3 Steering Analysis

The Eco-marathon vehicle does not encounter high speeds and is required a minimum turning radius of 8 meters. The turning radius will be calculated by using the Ackermann steering geometry. Rolling resistance is determined by using the rolling resistance coefficient. This will determine the choice of our engine, wheel and tire size.

3.3.1. Ackermann Steering Geometry

The course will have a few turns so we need to calculate the required radius to make the turn. To determine the radius, Ackermann steering geometry is used. Ackermann geometry is used to solve the problem of slippage of the tires when following the path of the turn. At low speed the wheels primarily roll without slip angle. The Ackermann steering geometry works by turning the steering pivot points to the inside, so there is a line drawn from the kingpin to the center of the rear tire [7]. The steering pivot point is joined by the tire rods and sometimes includes the rack and pinion. To calculate the radius, the wheels will have a common center point. The center point is an extended line from the rear axle as shown in Figure 3.4. It intersects with extended lines from the front axles while the wheels are turned inwards. Correct Ackermann steering reduces tire wear and is easy on terrain [9].

$$\cot\delta_o - \cot\delta_i = \frac{w}{l}$$

δ_i is the steering angle of the inner wheel.

δ_o is the steering angle of the outer wheel.

w is the distance between the steer axes of the steering wheel (track).

l is the distance between the front and rear axles (wheelbase).

The inner and outer steer angles δ_i and δ_o can be calculated by:

$$\tan\delta_i = \frac{l}{R_1 - \frac{w}{2}}$$

$$\tan\delta_o = \frac{l}{R_1 + \frac{w}{2}}$$

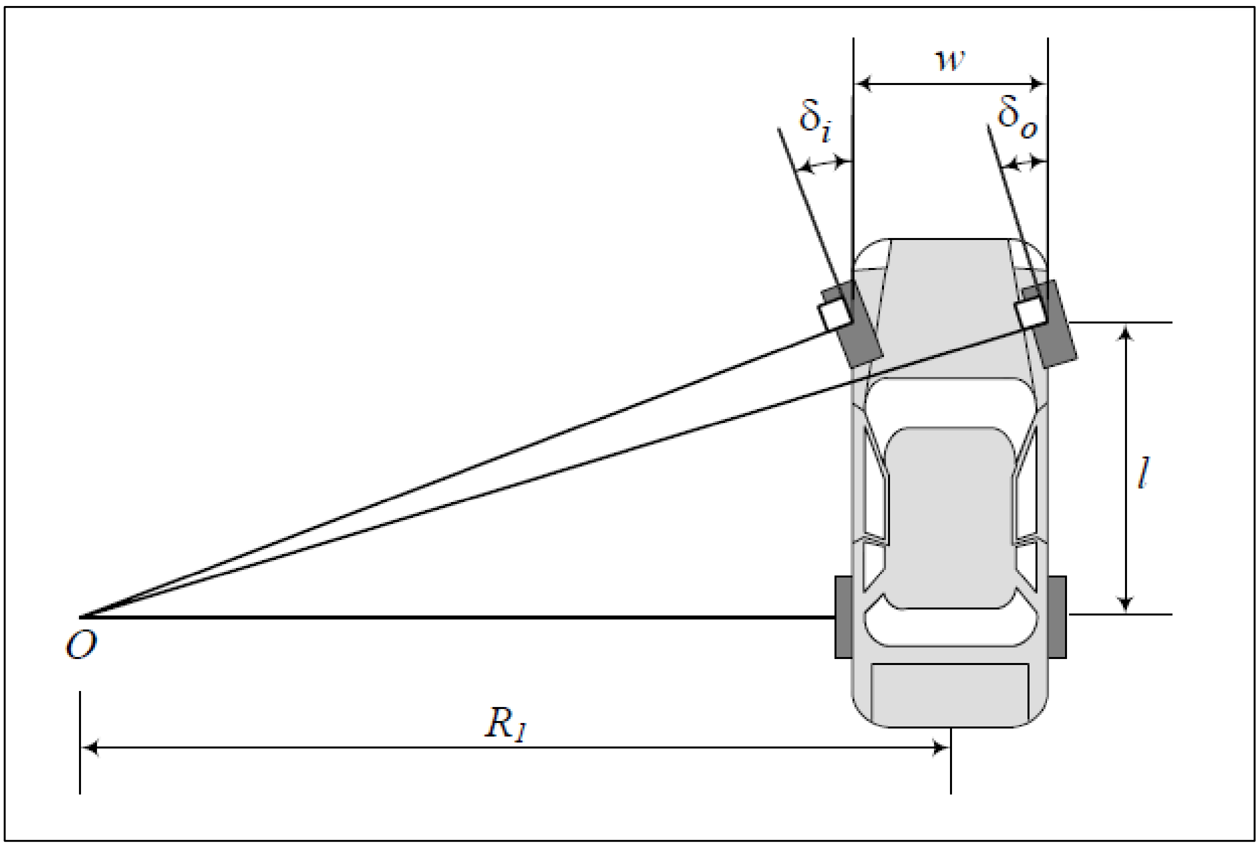

Figure 3.4: Front-Wheel Steering and the Ackermann Condition

The mass center of a steered vehicle will turn on a circle with radius R:

$$R = \sqrt{a_2^2 + l^2 \cot^2 \delta}$$

The track also known as the width (w) was given in the rule book, as shown in Figure 5. The width of the vehicle must be between 100 cm to 130 cm. The wheelbase also known as length (l) is required to be, between 220 cm – 230cm.

With delta calculated, R is calculated by the equation above. The center of mass (a) equals 120cm. Using an excel spreadsheet, the maximum value of R is l equal to 100cm and w equal to 350cm. Radius (r) equal to 11.98m. The minimum requirement is 8 m so anything above will work. A diagram of steering angles is shown in Figure 3.5.

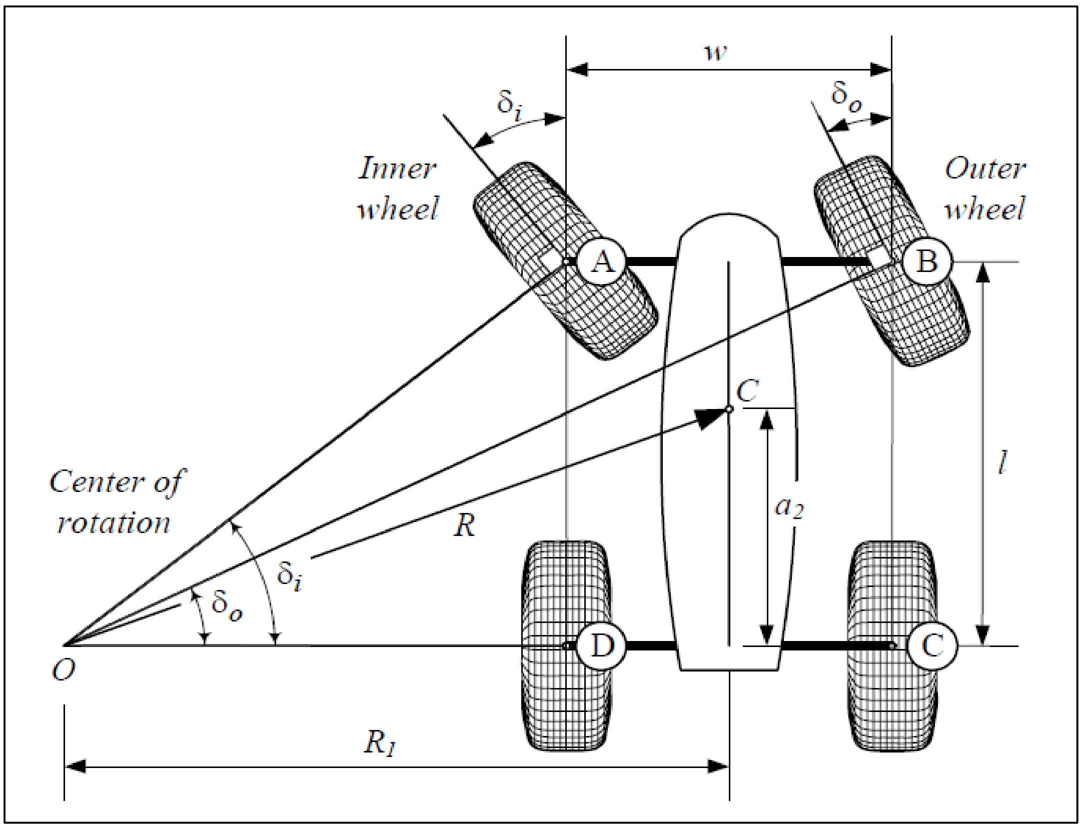

Figure 3.5: Steering Angles of Inner and Outer Wheels

3.3.2. Rolling Resistance

Rolling resistance is the force resisting the motion when a body (such as a tire, wheel or ball) rolls on a surface. Hysteresis is the main cause of rolling resistance. Hysteresis is when the energy of deformation is greater than the energy of recovery. The repeated cycle of the tire rotating results in loss if hysteresis, this is the main cause of energy loss. To keep the vehicle moving and above required speed the rolling resistance coefficient is used [9]. In determining the rolling resistance coefficient, the suffice engine size will be selected. Also, the rolling friction will be minimized. Factors that affect rolling resistance are tire pressure, tire diameter, tire thread. The higher the tire pressure the less deformation so there is less rolling resistance. The smaller diameter of tire the higher rolling resistance. The wider the tire the less rolling resistance. The smoother the tire thread, the better rolling resistance. The rolling resistance coefficient is determined by:

$$F = C_{\pi} N$$

Where F is the rolling resistance force, C_{rr} is the dimensionless rolling resistance coefficient, and N is the normal force, the force perpendicular to the surface on which the wheel is rolling. The coefficient of rolling friction can be calculate by:

$$C_{\pi} = {}^{z}/_{d}{}^{1/2}$$

Where *z* is the sink depth and *d* is the diameter of the rigid wheel. Tires that have done well in the past competition had diameter of 20 inches. The coefficient of rolling friction (C_{rr}) is 0.0055. Torque is the amount of force needed to rotate an object about an axis [10]. To determine the torque needed, we use the equation:

$$T = F_r r \quad [11]$$

Where F_r is the rolling resistance coefficient and r is the radius of the wheel.

3.4 Braking Analysis

The Shell Eco-marathon competition rulebook states that each braking system must hold the car and driver in place on a 20% grade slope. A 20% grade slope translates to 11.31˚.This is our main constraint for braking. Along with meeting the parking constraint, the weight of the braking system needs to be minimized in order to maximize fuel efficiency. The following analysis on the braking system is modeled after an article on the physics of braking systems [12]. The article was published by a braking design company called StopTech Systems.

The weight of the driver and car is assumed to be concentrated at a single point load of 1128 N located 1.2 meters away from the rear edge of the car and 0.27 meters above the bottom of the car. Zero slip is assumed to be between the wheels and the road. All mechanical components are assumed to be rigid with 100% efficiency. The free body diagram shown in Figure 3.6 shows the distributed forces on the car.

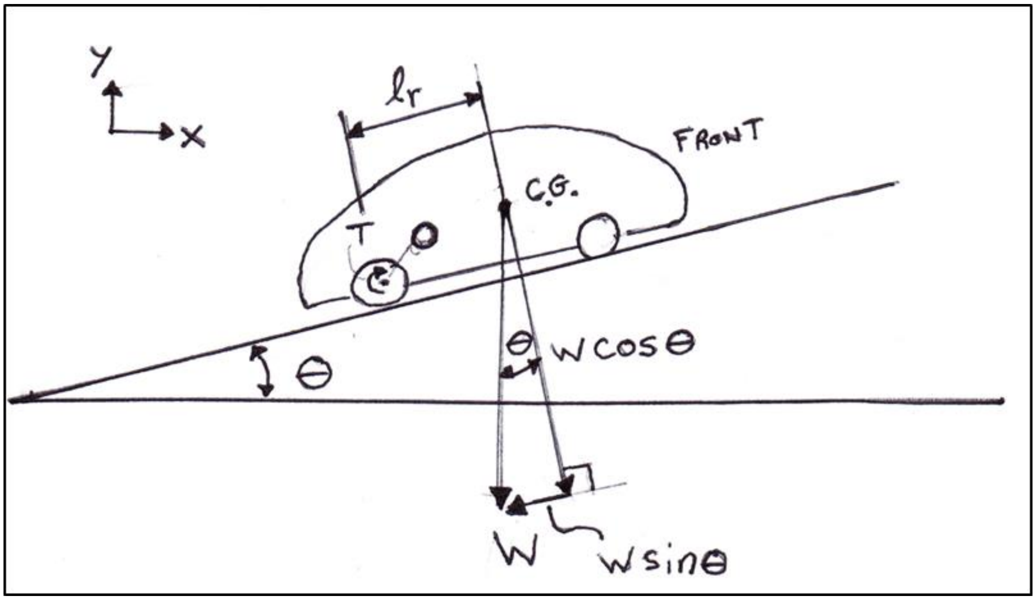

Figure 3.6: Braking Free Body Diagram

Shell requires at least two independent braking systems for each vehicle. Each braking system is required to hold the weight of the car on a 20% grade slope. The rear braking needs to provide more force than the front braking system. This is due to a larger distance between the car's center of gravity and the rear braking system than the distance between the center of gravity and the front braking system. This results in a larger toque on the rear braking system. The rear braking system only consists of one set of calipers rather than two sets on the front braking system.

Summing the moments around point O shows the required parking torque. The parking torque required by the rear braking, *Tr*, is equal to the tangent component of the weight, *wsinθ*, multiplied by the distance between the car's center of gravity and the rear axle, l_r.

Rear Braking Torque $$Tr = l_r w \sin\theta \tag{4.1}$$

From a closer look at the rear rotor, the torque needed to keep the car in place is determined by the clamping force of the calipers. The free body diagrams shown in Figure 3.7 and Figure 3.8 show this information.

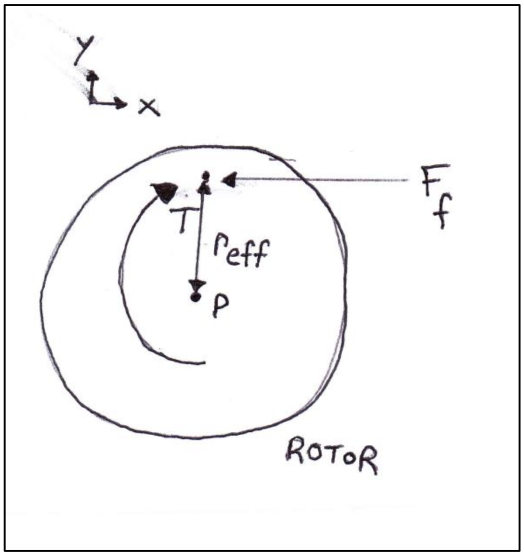

Figure 3.7: Rotor FBD

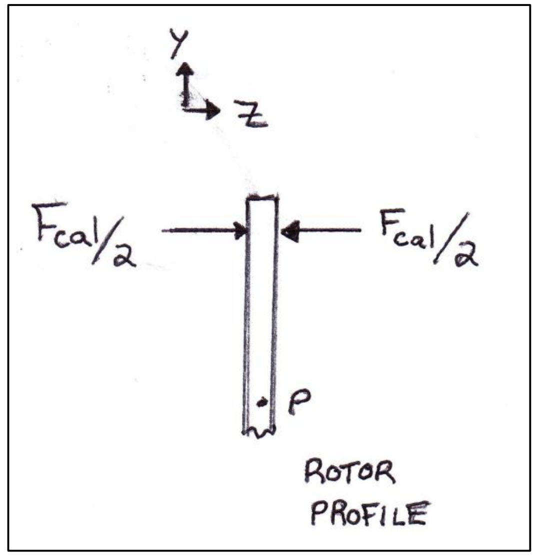

Figure 3.8: Rotor Profile FBD

Summing the moments around point P shows that torque on the rotor from the weight of the car, *Tr*, is equal to the friction force provided by the calipers, F_f, multiplied by the effective radius between the center of the rotor and the center of the caliper, r_{eff}.

$$Tr = F_f r_{eff} \tag{4.2}$$

The friction force from the caliper, F_f, is equal to the forces of both sides of the caliper multiplied by the coefficient of friction between the brake pad of the caliper and the rotor, μ_{bp}.

$$F_f = \mu_{bp} F_{cal} \tag{4.3}$$

From military standard 1472F, which includes standards for human design, the 5th percentile grip strength on a lever at 5π/6 degree elbow flexion is 222 Newtons for the left hand, as shown in Figure 3.9 and Table 3.3 [8].

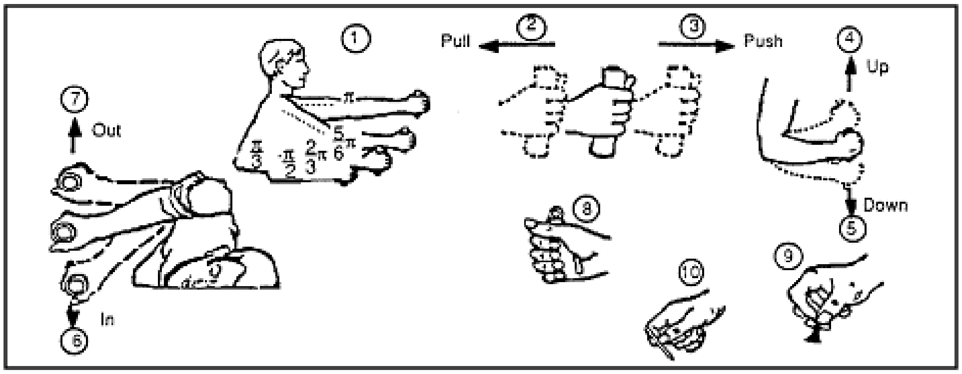

Figure 3.9: Arm, Hand, and Thumb/Finger Strength (5th Male Percentile)

Table 3.3: Hand and Thumb-Finger Strength

(1)	(2)		(3)		(4)		(5)		(6)		(7)	
Degree of elbow flexion (rad)	**Pull**		**Push**		**Up**		**Down**		**In**		**Out**	
	L**	R**	L	R	L	R	L	R	L	R	L	R
π	222	231	187	222	40	62	53	75	58	89	36	62
5/6 π	187	249	133	187	57	80	80	89	67	89	36	67
2/3 π	151	137	116	160	76	107	93	116	89	98	45	67
1/2 π	142	165	98	160	76	89	93	116	71	80	45	71
1/3 π	116	107	96	151	67	89	80	89	76	89	53	76
	Hand and thumb-finger strength (N)											

The left hand number is used for the analysis because it is typically the weaker hand and thus our minimum force exerted on the lever arm. Assuming 100% mechanical efficiency between the braking lines and components, the force by one side of caliper onto the rotor, F_{cal} is equal to the left hand lever force, F_l, multiplied by the ratio of the applied force radius, r_{force}, and the radius of the lever arm, r_{arm}.

$$F_{cal} = F_l \frac{r_{force}}{r_{arm}}$$

The mechanical clamping force due to the both sides of the caliper is equal to twice the force from one side.

$$F_{clamp} = 2 \text{ X } F_{cal}$$

The coefficient of friction can be calculated from combining equations (4.1), (4.2), and (4.3), while substituting the known values of F_{cal}, w, l_r, θ, r_{eff}.

$$\mu_{bp} F_{clamp} r_{eff} = l_r w \sin\theta$$

$$\mu_{bp}(9768\text{N})(.070\text{m}) = (1.2 \text{ m})(1128 \text{ N}) \sin(11.31°)$$

From the previous equation, μ_{bp} = .388, which is the minimum coefficient of friction needed to hold the car in place. The brake pad friction coefficient for semi-metallic brake pads ranges from 0.26 -0.38. Semi-metallic brake pads for bikes are cheaper than organic or carbon brake pads. NAU's previous Shell Eco-marathon car used MX2 brakes made by Hayes. Each braking component weighs 340 g, which compares to most high performance brakes and satisfies the objective for the current design. Standard sizes for rotors are 160mm, 185mm, and 203mm. The size of the rotor depends on weight and the applied forces onto the rotor. Smaller rotor sizes are beneficial because they are light weight. The rotors used on the previous car are 160mm in diameter and made from aluminum, which is perfect for the current design.

Chapter 4: Economic Analysis

4.1 Introduction

Steering and braking costs listed are arbitrary assumptions based on current market prices of bike components that could be used in final production. Components such as steering knuckles and steering uprights have not been designed so it is difficult to estimate the final cost of these components. Braking components will likely be reused from last year's Eco-marathon vehicle to reduce the initial production cost of the current vehicle.

The overall cost of fairing and chassis fabrication is unknown. High strength to weight ratio fairing materials would be cost prohibitive to purchase on our teams current budget and since none of the team are well versed in composite manufacturing the labor would also have to be outsourced to some degree. If material donations cannot be secured the fairing will likely be constructed from plain weave fiberglass. Frame welding must be done by a competent TIG welder which we do not have on our team. Thus the frame will likely be built in 98c and the welding done by the machine shop employees. The overall cost of this labor is currently unknown.

Table 3.4 is a sample bill of materials that will be expanded on as the design progresses.

4.2 Bill of Materials

Table 3.4: Bill of Materials

	Part	Type	Supplier	Cost
Chassis/Fairing	1.00X.083 Aluminum Round Tubing 40ft	26941.1	Online Metal Supply	$150.00
	Floorboard Brackets	SWPart: FloorboardBracket	Qty.Required 15	$60.00
	Fairing Material			
	Flooring Material	Carbon Floorboard/Nomex Honeycomb Core	AirTraining Group	
Safety Equipment	Fire Suit		GForce	$130.00
	Helmet		GForce	$150.00
	Gloves		GForce	$65.00
	20lb Fire Extinguisher			$115.00
	2.5lb Fire Extinguisher			$30.00
	5 Point Harness			$60.00
Braking/Steering	Brake Rotors			$60.00
	Brake Calipers			$150.00
	Steering Rack			$90
	Brake/Throttle Cable			$40.00
Wheels/Tires	Hubs			
	Rims			210
	Spokes			
	Front Tires			158
	Rear Tire	Michelin 44-406 Prototype	ecomarathonamericas@shell.com	$79.00
	Tubes			$60.00

4.3 Summary

As mentioned current labor estimates are unknown. The component cost is currently $2670. As more components are finalized and the materials specified for construction the cost of production will increase.

Chapter 5: Conclusion

The chassis will be designed with the driver as far reclined as possible while still maintaining adequate visibility and comfort. By minimizing the projected area on the front plane the aerodynamic drag at lower speed is negligible.

The fairing, as designed, exhibits very little deflection under the applied loads. With internal structures and seat supports added, the structure would only become more rigid.

Steering turn radius required by rules and regulation should be a minimum of 8 meters. Appendix B shows the calculation of track width (w) divided by wheelbase (l). Anything over 8 meters is acceptable. The main braking constraint is that each braking system needs to hold the car in place on a 20% grade slope. Most mountain bike disc brake systems provide enough force to hold the car at the given slope. Semi-metallic brake pads are the most ideal material for the braking system due to their relatively low cost, medium ranged friction coefficient, and their durability. The rotors from the previous year car will work at 160mm.

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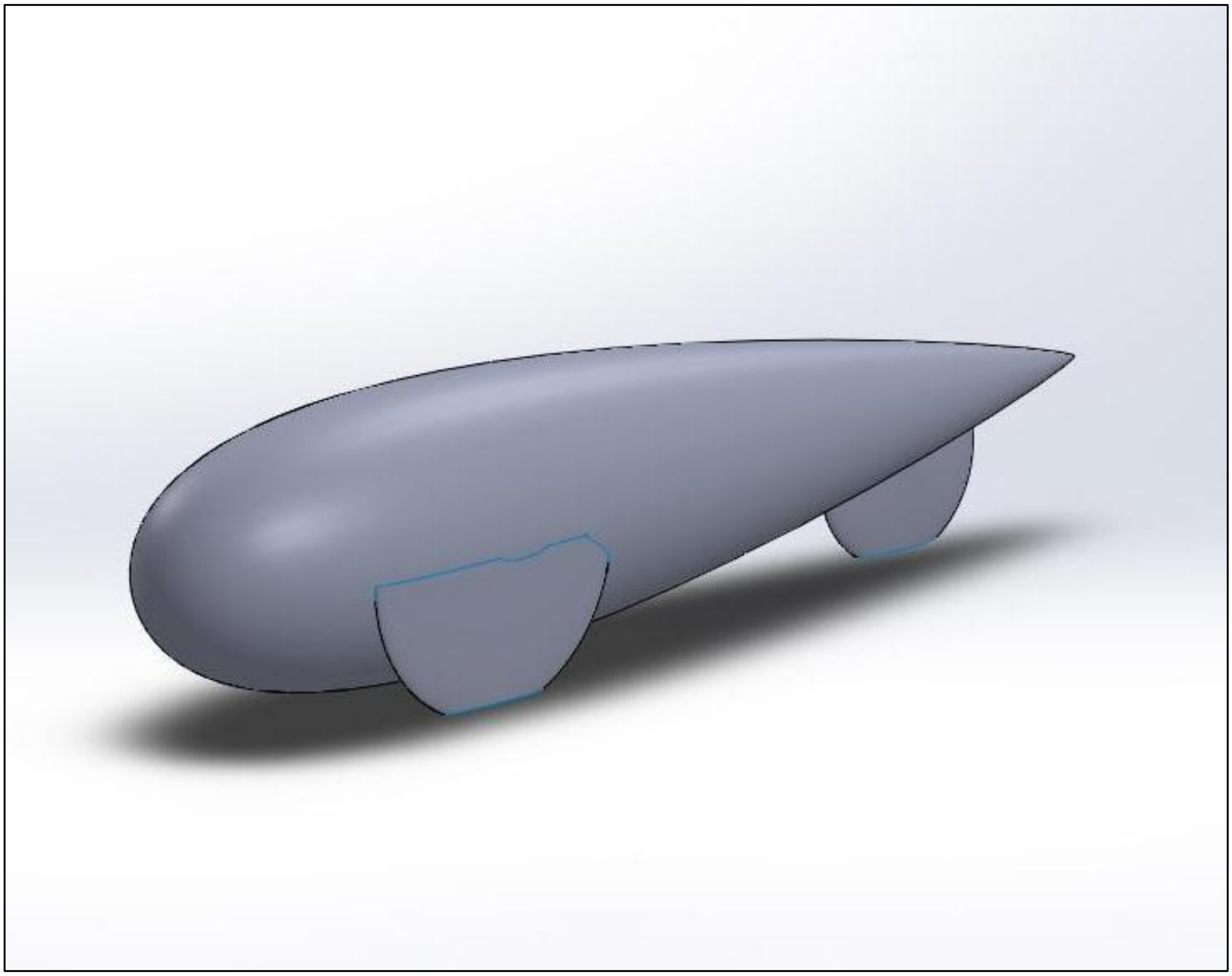
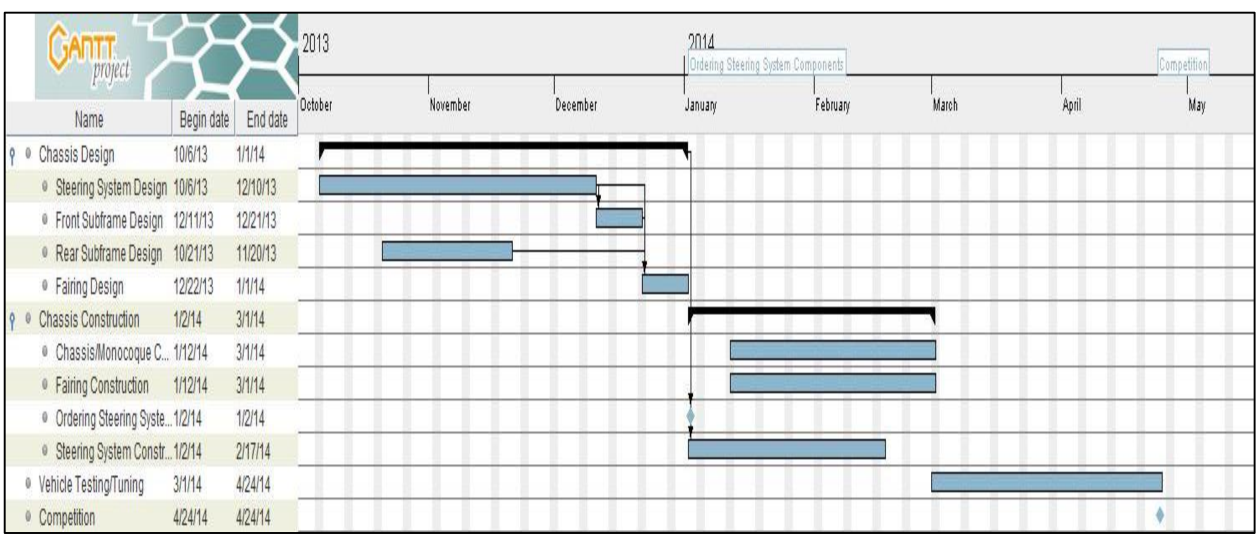
Appendix A



Appendix B



Appendix C

δ = w/l		Wheelbase l (cm)											
		240	250	260	270	280	290	300	310	320	330	340	350
	100	0.416667	0.4	0.384615	0.37037	0.357143	0.344828	0.333333	0.322581	0.3125	0.30303	0.294118	0.285714
	101	0.420833	0.404	0.388462	0.374074	0.360714	0.348276	0.336667	0.325806	0.315625	0.306061	0.297059	0.288571
	102	0.425	0.408	0.392308	0.377778	0.364286	0.351724	0.34	0.329032	0.31875	0.309091	0.3	0.291429
	103	0.429167	0.412	0.396154	0.381481	0.367857	0.355172	0.343333	0.332258	0.321875	0.312121	0.302941	0.294286
	104	0.433333	0.416	0.4	0.385185	0.371429	0.358621	0.346667	0.335484	0.325	0.315152	0.305882	0.297143
	105	0.4375	0.42	0.403846	0.388889	0.375	0.362069	0.35	0.33871	0.328125	0.318182	0.308824	0.3
	106	0.441667	0.424	0.407692	0.392593	0.378571	0.365517	0.353333	0.341935	0.33125	0.321212	0.311765	0.302857
	107	0.445833	0.428	0.411538	0.396296	0.382143	0.368966	0.356667	0.345161	0.334375	0.324242	0.314706	0.305714
	108	0.45	0.432	0.415385	0.4	0.385714	0.372414	0.36	0.348387	0.3375	0.327273	0.317647	0.308571
	109	0.454167	0.436	0.419231	0.403704	0.389286	0.375862	0.363333	0.351613	0.340625	0.330303	0.320588	0.311429
track w (cm)	110	0.458333	0.44	0.423077	0.407407	0.392857	0.37931	0.366667	0.354839	0.34375	0.333333	0.323529	0.314286
	111	0.4625	0.444	0.426923	0.411111	0.396429	0.382759	0.37	0.358065	0.346875	0.336364	0.326471	0.317143
	112	0.466667	0.448	0.430769	0.414815	0.4	0.386207	0.373333	0.36129	0.35	0.339394	0.329412	0.32
	113	0.470833	0.452	0.434615	0.418519	0.403571	0.389655	0.376667	0.364516	0.353125	0.342424	0.332353	0.322857
	114	0.475	0.456	0.438462	0.422222	0.407143	0.393103	0.38	0.367742	0.35625	0.345455	0.335294	0.325714
	115	0.479167	0.46	0.442308	0.425926	0.410714	0.396552	0.383333	0.370968	0.359375	0.348485	0.338235	0.328571
	116	0.483333	0.464	0.446154	0.42963	0.414286	0.4	0.386667	0.374194	0.3625	0.351515	0.341176	0.331429
	117	0.4875	0.468	0.45	0.433333	0.417857	0.403448	0.39	0.377419	0.365625	0.354545	0.344118	0.334286
	118	0.491667	0.472	0.453846	0.437037	0.421429	0.406897	0.393333	0.380645	0.36875	0.357576	0.347059	0.337143
	119	0.495833	0.476	0.457692	0.440741	0.425	0.410345	0.396667	0.383871	0.371875	0.360606	0.35	0.34
	120	0.5	0.48	0.461538	0.444444	0.428571	0.413793	0.4	0.387097	0.375	0.363636	0.352941	0.342857
	121	0.504167	0.484	0.465385	0.448148	0.432143	0.417241	0.403333	0.390323	0.378125	0.366667	0.355882	0.345714
	122	0.508333	0.488	0.469231	0.451852	0.435714	0.42069	0.406667	0.393548	0.38125	0.369697	0.358824	0.348571
	123	0.5125	0.492	0.473077	0.455556	0.439286	0.424138	0.41	0.396774	0.384375	0.372727	0.361765	0.351429
	124	0.516667	0.496	0.476923	0.459259	0.442857	0.427586	0.413333	0.4	0.3875	0.375758	0.364706	0.354286
	125	0.520833	0.5	0.480769	0.462963	0.446429	0.431034	0.416667	0.403226	0.390625	0.378788	0.367647	0.357143
	126	0.525	0.504	0.484615	0.466667	0.45	0.434483	0.42	0.406452	0.39375	0.381818	0.370588	0.36
	127	0.529167	0.508	0.488462	0.47037	0.453571	0.437931	0.423333	0.409677	0.396875	0.384848	0.373529	0.362857
	128	0.533333	0.512	0.492308	0.474074	0.457143	0.441379	0.426667	0.412903	0.4	0.387879	0.376471	0.365714
	129	0.5375	0.516	0.496154	0.477778	0.460714	0.444828	0.43	0.416129	0.403125	0.390909	0.379412	0.368571
	130	0.541667	0.52	0.5	0.481481	0.464286	0.448276	0.433333	0.419355	0.40625	0.393939	0.382353	0.371429

R =[a^2 + l^2+cot^2δ]^(1/2)		Wheelbase l (cm)											
		240	250	260	270	280	290	300	310	320	330	340	350
	100	555.8287	603.7601	653.8165	705.9791	760.2327	816.5646	874.9643	935.423	997.9331	1062.488	1129.083	1197.714
	101	549.9294	597.3639	646.9048	698.5335	752.2344	807.9947	865.8038	925.6528	987.5339	1051.441	1117.368	1185.311
	102	544.1422	591.089	640.1245	691.2294	744.3883	799.5882	856.8181	916.0691	977.3335	1040.605	1105.878	1173.147
	103	538.4637	584.9322	633.4716	684.0629	736.6901	791.3401	848.002	906.6666	967.3261	1029.974	1094.605	1161.214
	104	532.8909	578.8899	626.9427	677.0299	729.1355	783.2461	839.3507	897.44	957.5062	1019.543	1083.544	1149.505
	105	527.4207	572.9588	620.5341	670.1266	721.7203	775.3016	830.8594	888.3843	947.8684	1009.305	1072.688	1138.013
	106	522.0502	567.1359	614.2423	663.3494	714.4406	767.5025	822.5237	879.4947	938.4075	999.2552	1062.032	1126.733
	107	516.7766	561.4182	608.0643	656.6947	707.2927	759.8447	814.3392	870.7665	929.1185	989.3885	1051.57	1115.659
	108	511.5973	555.8026	601.9967	650.1591	700.2729	752.3243	806.3016	862.1952	919.9968	979.6995	1041.297	1104.785
	109	506.5096	550.2865	596.0366	643.7393	693.3776	744.9374	798.407	853.7765	911.0377	970.1835	1031.208	1094.106
	110	501.5111	544.867	590.181	637.4322	686.6035	737.6805	790.6514	845.5063	902.2367	960.8356	1021.297	1083.616
	111	496.5994	539.5416	584.4271	631.2348	679.9473	730.55	783.0311	837.3805	893.5897	951.6514	1011.56	1073.309
	112	491.7722	534.3078	578.7723	625.1441	673.4058	723.5426	775.5425	829.3953	885.0924	942.6265	1001.992	1063.182
	113	487.0272	529.1632	573.2138	619.1573	666.976	716.655	768.182	821.5469	876.7409	933.7566	992.588	1053.23
track w (cm)	114	482.3622	524.1054	567.7491	613.2717	660.6549	709.8839	760.9464	813.8317	868.5313	925.0377	983.3446	1043.447
	115	477.7752	519.1321	562.3759	607.4845	654.4398	703.2265	753.8322	806.2464	860.4601	916.4658	974.2573	1033.829
	116	473.2643	514.2412	557.0917	601.7934	648.3278	696.6798	746.8365	798.7874	852.5235	908.0371	965.322	1024.373
	117	468.8273	509.4306	551.8943	596.1958	642.3164	690.2408	739.9561	791.4516	844.7181	899.748	956.5349	1015.073
	118	464.4626	504.6982	546.7814	590.6893	636.403	683.907	733.1882	784.2358	837.0406	891.5949	947.8921	1005.927
	119	460.1682	500.0421	541.751	585.2717	630.5851	677.6756	726.5299	777.137	829.4878	883.5743	939.39	996.9291
	120	455.9424	495.4604	536.8009	579.9407	624.8604	671.5441	719.9784	770.1524	822.0565	875.683	931.0251	988.077
	121	451.7835	490.9512	531.9293	574.6942	619.2265	665.5099	713.5312	763.279	814.7438	867.9178	922.794	979.3668
	122	447.69	486.5127	527.1341	569.5302	613.6812	659.5708	707.1856	756.5141	807.5468	860.2755	914.6935	970.7948
	123	443.6601	482.1434	522.4136	564.4465	608.2223	653.7244	700.9392	749.8551	800.4625	852.7532	906.7202	962.3578
	124	439.6924	477.8414	517.7658	559.4414	602.8478	647.9685	694.7896	743.2994	793.4883	845.3479	898.8713	954.0524
	125	435.7854	473.6051	513.1892	554.5128	597.5556	642.3008	688.7344	736.8446	786.6215	838.0569	891.1435	945.8755
	126	431.9377	469.4331	508.6819	549.659	592.3439	636.7194	682.7715	730.4882	779.8596	830.8774	883.5342	937.8241
	127	428.1478	465.3238	504.2424	544.8783	587.2106	631.2221	676.8985	724.2279	773.2002	823.8068	876.0404	929.8951
	128	424.4144	461.2758	499.8691	540.1688	582.1539	625.807	671.1136	718.0615	766.6407	816.8425	868.6596	922.0857
	129	420.7363	457.2876	495.5604	535.529	577.1721	620.4722	665.4145	711.9868	760.1789	809.9821	861.3889	914.3932
	130	417.1121	453.3578	491.3149	530.9573	572.2635	615.2158	659.7993	706.0017	753.8126	803.2232	854.226	906.8147