NAU Shell Eco-Marathon
Team

Memo

To: Dr. John Tester

From: Abdul Alshodokhi, Moneer Al-Jawad, Jericho Alves, John Gamble, Nikolaus Glassy, Benjamin Kurtz, & Travis Moore

Cc: Dr. Srinivas Kosaraju

Date: May 2, 2014

Re: Project Proposal

In the two semester, the team designed, built, and competed with a prototype vehicle for the Shell Eco-marathon competition.

The team's selected design involves using a small displacement 50 cc GY6-QMB engine produced by Honda. The GY6-QMB engine is integrated with a fuel injection kit from Ecotrons. This combination will give the team a great starting point to be able to precisely tune for maximum fuel efficiency. The vehicle's engine is attached to a centrifugal clutch and a custom 2-stage chain and sprocket drivetrain. The frame of the vehicle is made of 6061-T6 aluminum tubing. The frame is reinforced with Nomex honeycomb core carbon fiber panels. The fairing of the vehicle is made of 3 layers of fiberglass and an exterior layer of carbon fiber. Finally, the battery choice to power the electrical system will be a Deka ETX-9 battery. With these components, along with the other components from the other team, the NAU Shell Eco-Marathon Team predicts a target fuel economy of at least 550 miles per gallon.

The estimated cost for the vehicle is \$3,189. The maximum fuel mileage reached after testing and the competition was 114 mph.

Shell Eco-marathon

By
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Team 14

Final Report
Document

Submitted towards partial fulfillment of the requirements for
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Table of Contents

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

List of Figures

List of Tables

Abstract

The Shell Eco-marathon competition is designed to encourage research to produce fuel efficient vehicles. Our project team will participate in this event representing the Society for Automotive Engineers at Northern Arizona University. The team has designed and fabricated a prototype vehicle that can produce high fuel efficiency. The powertrain design of the car uses a 50cc gasoline engine coupled with a fuel injection system to improve fuel efficiency. The drivetrain system will employ a dual gear reduction to reduce rotating mass and achieve an average speed of 17 mph. A fiberglass fairing encompasses the entire vehicle to minimize drag. The maximum fuel efficiency calculated was approximately 800 mpg on a flat surface. During competition, our vehicle encountered numerous obstacles that resulted in a DNF (did not finish) for the NAU Eco Marathon team.

1. Introduction:

1.1. Background:

The Shell Corporation puts on an annual competition that focuses on increasing the efficiency of fossil fuel powered vehicles and increasing the interest as well as the efficiency of renewable energy vehicles. The competition will be held in Houston, TX in late April. The prototype vehicle that competes will have to meet the rules and regulations set out by Shell. The purpose of this project outlined by the team's client is to design, build, and compete well with a prototype vehicle that will achieve the highest fuel economy possible.

1.2. Client:

The primary client for this project is Dr. John Tester at Northern Arizona University (NAU). Dr. Tester is involved with the student chapter of Society of Automotive Engineers (SAE). Dr. Tester has been the academic advisor for the Shell Eco-Marathon for previous competitions. The secondary client for this project is the student chapter SAE because most of the funding is coming directly from the student chapter SAE's budget.

1.3. Need Statement:

Due to the significant number of vehicles running on finite resources as a means of transportation, it has become necessary to research and develop means to stretch those finite resources further. The Shell Corporation has sponsored a competition to promote this research and development in the field of fuel efficiency. The scope of this project is to design, build, test, and present a vehicle that conforms to the set requirements and constraints to produce a vehicle that will produce extremely high fuel efficiency.

2. Problem Formulation:

2.1. Goal:

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.

2.2. Operating Environment:

Our operating environment can be broken into 4 main sections: design, build, test, and competition. The bulk of design and fabrication work will be done at the NAU campus in Flagstaff, AZ. The design work will consist of weekly group and team meetings. This is to ensure that all of the team's member's independent work will be appropriate to the overall design and has yielded accurate results.

All of the fabrication of the design vehicle will be done at the student build shop located on the NAU campus. This is where the design vehicle will take form, having all of the separate systems coming together. The team will assemble ordered parts, fabricate custom parts, and install systems on the vehicle. The initial engine break in period will be performed here. The team's drivers will also gain experience driving and operating the integrated systems in the vehicle to ensure they are easy to operate.

The team will perform initial quality tests in Flagstaff, but will travel down to Phoenix, AZ to get a more accurate tune for the competition location. Since the competition is located in Houston, TX, elevation 43 feet above sea level, tuning the vehicle for Flagstaff's elevation of 7000 feet above sea level would not yield the best engine efficiency results come competition. Thus, the team will take the vehicle and tune it to an elevation of 1200 feet above sea level in Phoenix. The reasoning behind this is so that there will not be a severe change in tuning as compared to an extremely high elevation of 7000 feet.

The final operating environment will be the Shell Eco-Marathon Competition located in downtown Houston. Here the vehicle will be tuned and have several practice laps before the actual competition. This is also where the team will present the technical documentation for the vehicle.

2.3. Design Objectives:

Table XX shows the design objectives for this project. In order to increase vehicle efficiency, the vehicle must be lightweight, rigid, and aerodynamic. A lightweight vehicle will achieve higher fuel efficiency since there is less mass that the motor must move around. A rigid car will be safe for the driver. A car that minimizes aerodynamic drag will encounter less force while moving, allowing the vehicle to achieve a higher fuel efficiency. Additionally, this car must minimize cost. Since NAU is a smaller school, the financial resources available for this project are limited.

Table 2.1: Design Objectives

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

2.4. Design Constraints:

- Dimensional Constraints (Article 39)
  - Length: 350cm Maximum
  - Width: 130cm Maximum
  - Height: 100cm Maximum
  - Track Width: 50cm Minimum
  - Wheelbase: 100cm Minimum
  - Height/Width Ratio: 1.25 Maximum
- Chassis/Fairing 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 fairing 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.
  - 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.
- Drivetrain Constraints (Transmission & Clutch):
  - Effective transmission chain or belt guard(s):
    - Protect driver or technician
    - Made of metal or composite material
    - Rigid enough to withstand a break

- Manual Clutch:
    - Must not have the starter motor operable with the clutch engaged.
- Automatic clutch:
    - Motor starting speed below speed engagement of the clutch.

- Braking Constraints:
  - 2 Independent Systems
    - Front Wheel(s)
    - Rear Wheel(s)
  - All wheels must have braking force applied
  - Simultaneous Engagement
- Fuel System Constraints:
  - Fuel must be Shell Regular Gasoline (87) or E100 (100% Ethanol)
  - Fuel tank must be APAVE certified and a volume of either 30,100,or 250 cc
  - Fuel tank must be mounted in a zero degree position and at least 5cm below the roll bar
  - Air Intake must not contain any fuel or blow-by gas
  - Internal and external emergency shut-down systems must shutdown the ignition and fuel supply
  - External system must be permanently mounted to body
  - External system must have a latching red push button and be labeled with a 10cm by 3cm wide red arrow on a white background·
  - Fuel line between tank and engine may not contain any other elements
  - Fuel lines must be flexible and clear in color and not prone to expansion
  - Teams cannot increase or decrease the fuel temperature
  - Float chambers must include a drain valve at the bottom of the carburetor to ensure fuel level goes down in the fuel tank
- Electrical System Constraints:
  - Maximum on-board voltage must not exceed 48V nominal
  - Only one on-board battery and the battery must maintain a constant ground
  - Electrical circuits must be protected from short circuit and overload
  - Electric horn must be 85 dB and pitch of 429 Hz
  - Electrical starter can only operate when ignition and fuel systems are activated
  - Electrical starter must not provide propulsion
  - A red starter light must be installed on the rear of the vehicle with a luminescence of 21W and be clearly visible from both sides
  - Starter and starter light must be extinguished by the time the rear wheel crosses the start line
- Driver Safety
  - Seat Belt: it has to have 5 mounting point's meets all together in single buckle. Firmly, mounting points have to be attached to the vehicle main structure.
  - Helmet: full face or three quarters must be worn all the time inside the vehicle during practice or actual competition.
  - Vehicle Access: suitable space for driver so he/she can exit the vehicle without assistance. Besides, to have enough space for the driver's comfort.
  - Exhaust System: the exhaust gas must be evacuated outside of the vehicle to insure the safety of the driver.

- Insulation: engine must completely be insulated from the driver to eliminate the heat produced from the engine.
- Fire Extinguisher: must be on-board at all time
- Each vehicle must have a valid hand held fire extinguisher and driver must acknowledge the use.

- Vehicle Safety
  - Inspection: vehicle will be inspected by the organizer to ensure the safety of the components.
    - Parts: must be firmly attached together.
    - Frame: must be settled and installed correctly.
    - Chassis: must be rigid.
        - Brakes: two braking systems must be installed independently to increase the efficiency and to secure the vehicle.
    - System 1 must act on the front wheels only.
    - System 2 must act on the rear wheels only.
  - Emergency Shut-Down System: vehicle must have two independent shut-down switches. Both must be operable from the interior driver position and the exterior of the vehicle.
  - Fire Extinguisher: must be on-board at all time.
  - Another fire extinguisher must be present in the team's garage area.
- Steering System
  - 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.
  - 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.
- Technical Documentation Constraints:
  - Fuel System
    - Full description and detailed schematic from tank to motor
      - Including pressurized air bottle, pressure relief valves, air pressure gauges, fuel tank, valves, injectors, float chambers, and pumps
    - Description of vehicle clutch operation
    - Specifically showing starter motor does not engage clutch
  - Electrical System

        - Circuit diagrams with all components listing voltage, current, and power ratings
            - Show emergency stop switch locations for inside and outside of car
            - Show battery location with type and rated voltage
            - Show starter motor location
    - All documentation must be current, have printed copies, and be displayed on a poster

3. Proposed Design

3.1 Chassis and Fairing

The proposed design consists of a tube frame chassis constructed out of aluminum. The frame would run the length of the vehicle and support all steering and driveline components as well as the roll bar. The main benefit of this design is that we can manufacture the entire frame in house with the aid of NAU staff, and it is inexpensive compared to a composite monocoque construction. The fairing can be made from a single plug and mold. The fairing is made from composite materials and fitted over the frame. Figure 3.1 shows a SolidWorks sketch of the proposed frame.

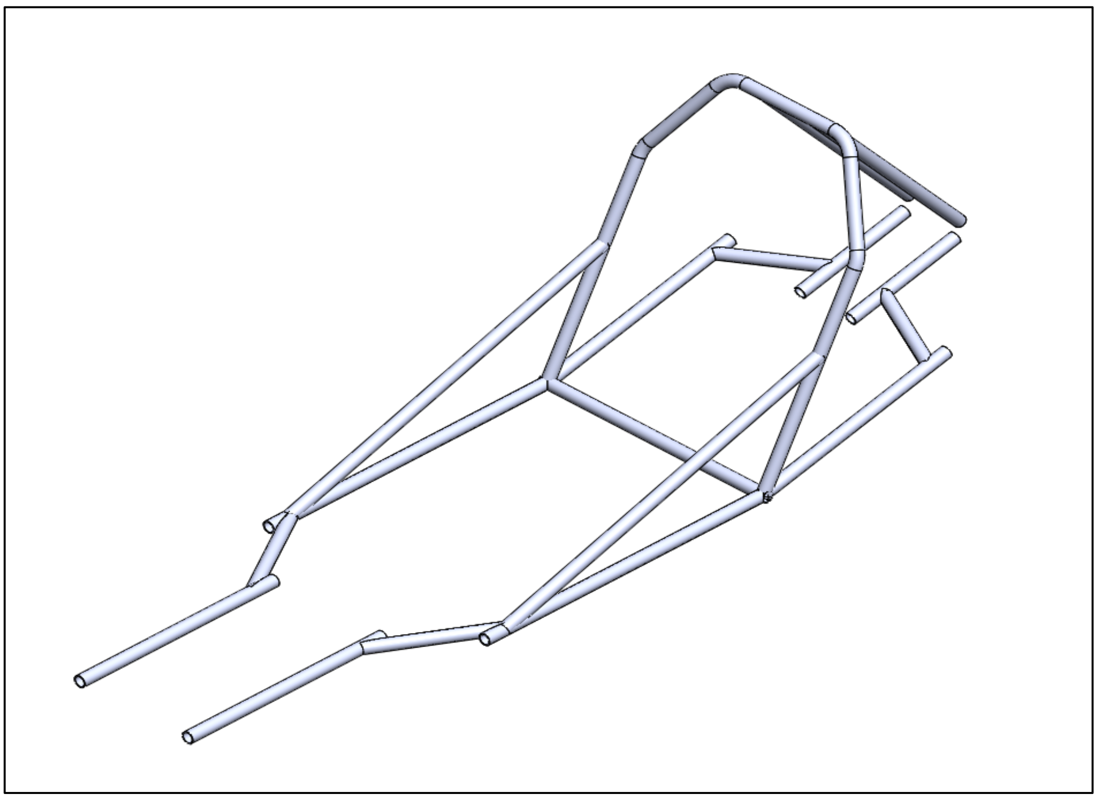


Figure 3.1: SolidWorks Sketch of Proposed Frame Design

3.1.1. Chassis and Fairing Engineering 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 [1]. 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 3.2 below.

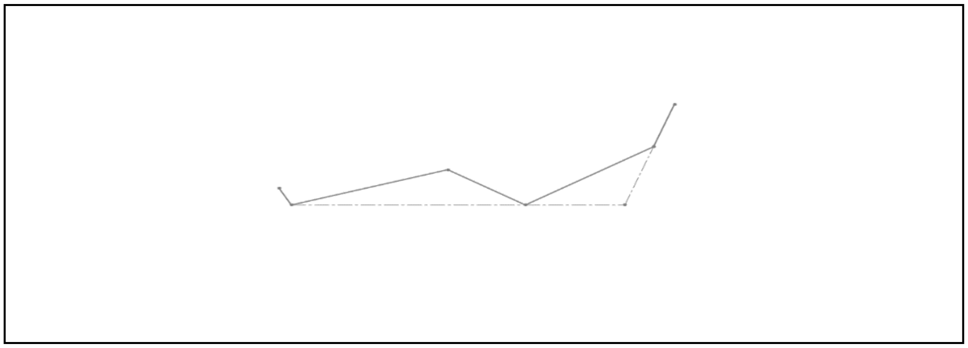


Figure 3.2: Driver Position Diagram

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 3.3 below.

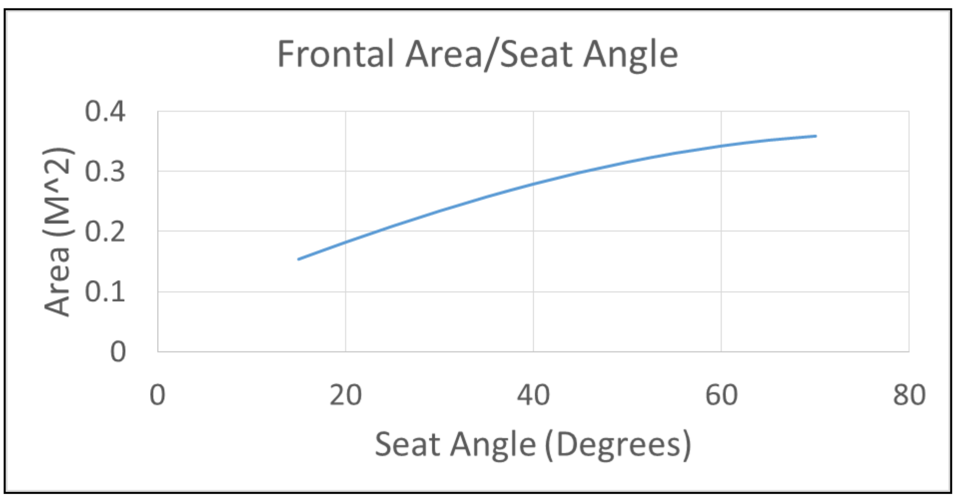


Figure 3.3: Frontal Area/Seat Angle

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 3.4.

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

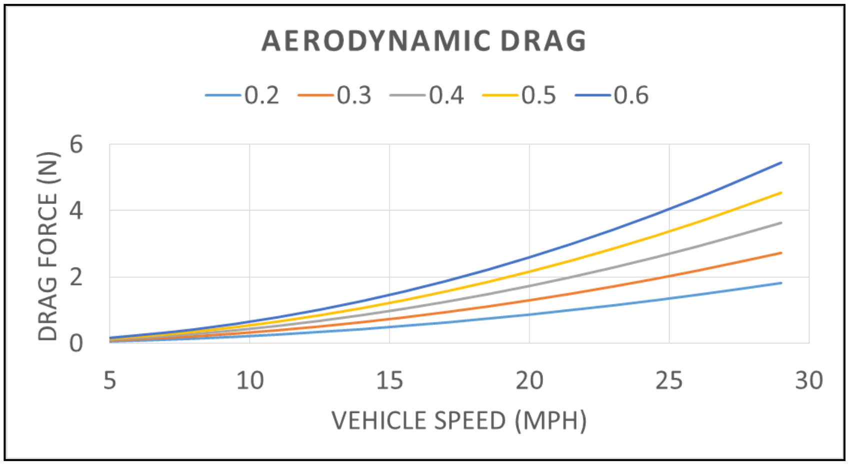


Figure 3.4: Force of Aerodynamic Drag

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.

3.1.2. Fairing 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

3.2. Steering, Wheels, and Brakes

Steering

The proposed steering design uses a pitman arm setup with a quick steering ratio. The pitman arm reduces the amount of effort necessary from the driver to turn the front wheels. The quick steering ratio allows the driver to only use minimal movement to steer the car. Making it so that only minimal input is necessary from the driver to steer the car minimizes the amount of space necessary for the driver to operate the car and, consequently, minimize vehicle size.

The proposed steering design was to have a cross member located in front of the vehicle and the uprights installed at the each end as shown in figure 3.5. The steering arms will be attached to the uprights so the tires can be placed into the proper location. The steering column will be mounted in the middle of the cross member. The steering column will be attached directly to the steering rod and the tie rods will be attached to the steering column. This arrangement will allow the vehicle to turn left or right as needed. The operating mechanism of this system is simple, whenever the driver is desired to make a turn, just simply turn the steering wheel. Since the steering column is attached directly to the steering rod, the tie rods will push the steering arm in the correct direction.

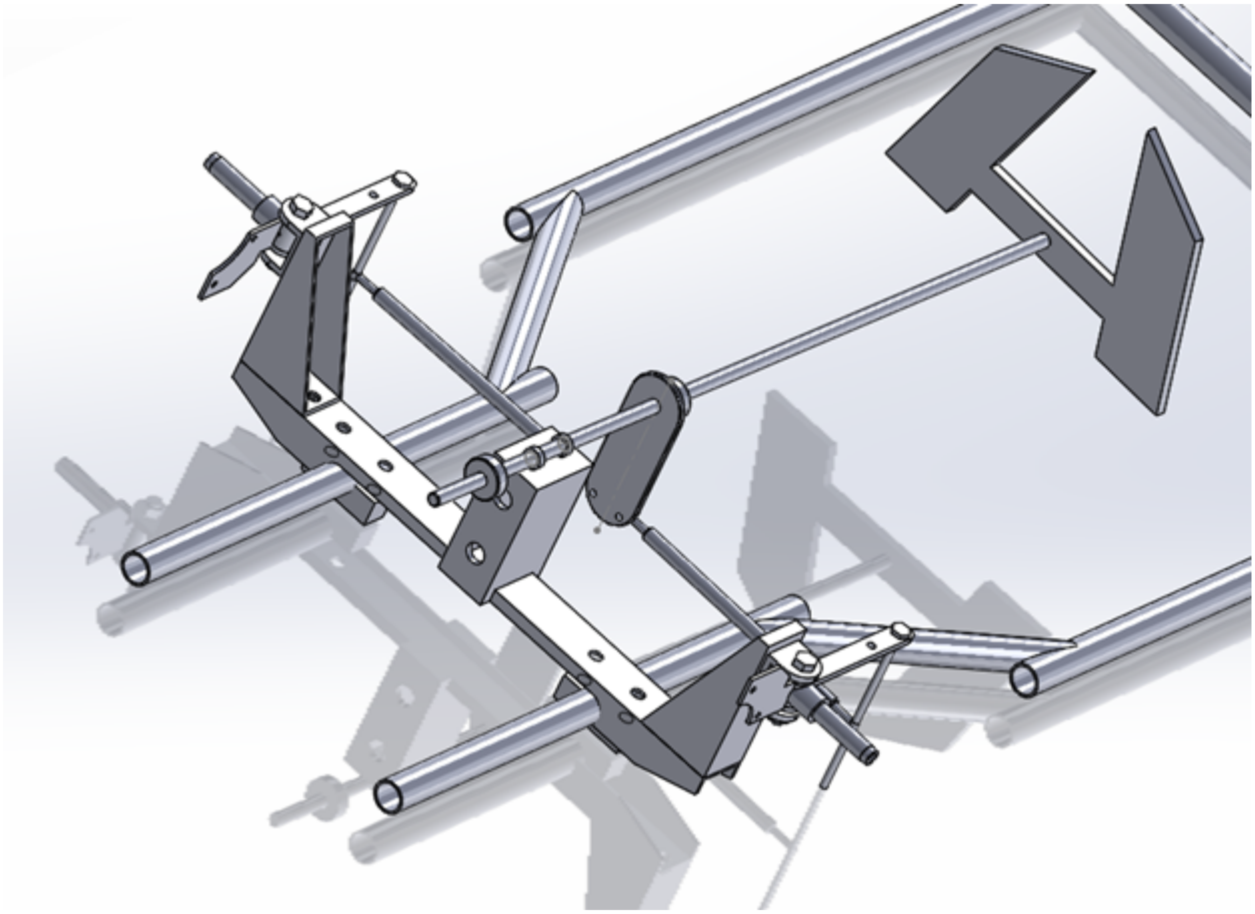


Figure 3.5: Proposed Steering Design

Wheels

The car uses a 3 wheel design with 2 wheels in the front and one larger wheel in the rear. The wheels selected to be used for the car were from bicycles: 16” x 1-3/8” for the front wheels and 20 x 1-1/2” for the rear wheel. These wheels were selected because they were already available to the team through SAE inventory.

Brakes

The braking system selected for the car design uses disc brakes from a bicycle. There are brakes applied to each of the front wheels, and 1 on the rear wheel. The front braking system operates independently from the rear braking system as per the rules set by Shell. Brakes are operated from controls inside the vehicle located on the steering wheel.

3.3. Engine

The engine selection for the Shell Eco-Marathon car is one of the most important aspects for the vehicle's success. Since the goal is to improve fuel efficiency, finding a motor that will be able to power the vehicle while using the least amount of power is important. Motor compression ratios are a way to improve engine efficiency. It is possible to improve engine compression by changing parts but using a motor that has a higher compression ratio to start with is a better option. As a small school, our budget is limited, so finding the best cost/performance ratio for the motor is important. Whatever motor was selected, fuel injection would be fitted to the engine because it would provide a more precise level of tuning and engine performance consistency. Honda engines were compared as possible motors to use because of their low cost and high reliability. The team considered a Honda GY6-QMB 50cc engine, a GX35 35cc engine, and a GX25 25cc engine. Table 3.3 shows the properties for these engines necessary for efficiency analysis.

Table 3.3: Engine Properties

_	(units measured)	Honda GX25	Honda GX35	Honda GY6-QMB
Displacement	cc	25	35	50
Compression Ratio	unitless	8	8	10.5
Power Output	kW	0.72	1	2.1
Torque Output	N-m	1	1.6	3.1
Intial Fuel Consumption	L/hr	0.54	0.71	1.04
Intial Fuel Consumption	gram/s	0.5243049	0.68936385	1.0097724
Fuel Consumption engine speed	RPM	7000	7000	6500
Fuel Consumption engine speed	Radians/s	732.6666667	732.6666667	680.3333333

Since all engines are 4 stroke, the air standard Otto cycle can be used to analyze their efficiencies. The Otto cycle efficiency analysis calculates the maximum possible efficiency for the engine considering its compression ratio. Equation _ for the thermodynamic efficiency is:

$$\eta = 1 - \frac{1}{r^{k-1}}$$

Where r is the compression ratio for the engine, and k is the specific heat ratio. For ambient air, k is equal to ~1.4 [2]. Using this equation, the calculated engine efficiencies can be found in Table 3.4.

Table 3.4: Otto Cycle Engine Efficiencies

η(GX25)	57%
η(GX35)	57%
η(GY6-QMB)	62%

As shown in Table 3.4, the GY6-QMB produces the highest efficiency among compared engines. Brake specific fuel economy is a measure of an engine's fuel consumption as a ratio with the amount of power reduced. BSFC is used as a measure of fuel efficiency while removing driving habits from consideration. Similarly to the air standard Otto cycle, BSFC does not provide real-world efficiency for the engine, but it does provide ratios between the 3 engines to compare their max possible efficiencies.

BSFC is calculated using equation 3.2 where r is fuel consumption in g/s, T is the torque produced by the engine in N-m, and ω is the engine speed in radians/s.

$$BSFC = \frac{r}{T \times \omega}$$

Using the properties from Table 3.5, the BSFC calculations can be found in Table _. For BSFC, the lower the value, the less fuel consumed per power produced.

Table 3.5: BSFC Calculations

BSFC(GX25)	0.00072
BSFC(GX35)	0.00059
BSFC(GY6-QMB)	0.00048

While the GY6 consumes the most fuel initially, it has superior fuel consumption considering the power produced.

The GY6 produces the highest possible efficiency in the Otto cycle using air standard analysis and consumes the least amount of fuel with the BSFC equation. Consequently, the GY6-QMB is the engine that will be used in our design.

Using the BSFC calculations, and estimates for coefficient of drag, frontal area, and rolling resistance, an estimation of fuel efficiencies for the 3 motors was produced. See Figure 3.6 for a plot of the projected fuel efficiencies of the 3 engines.

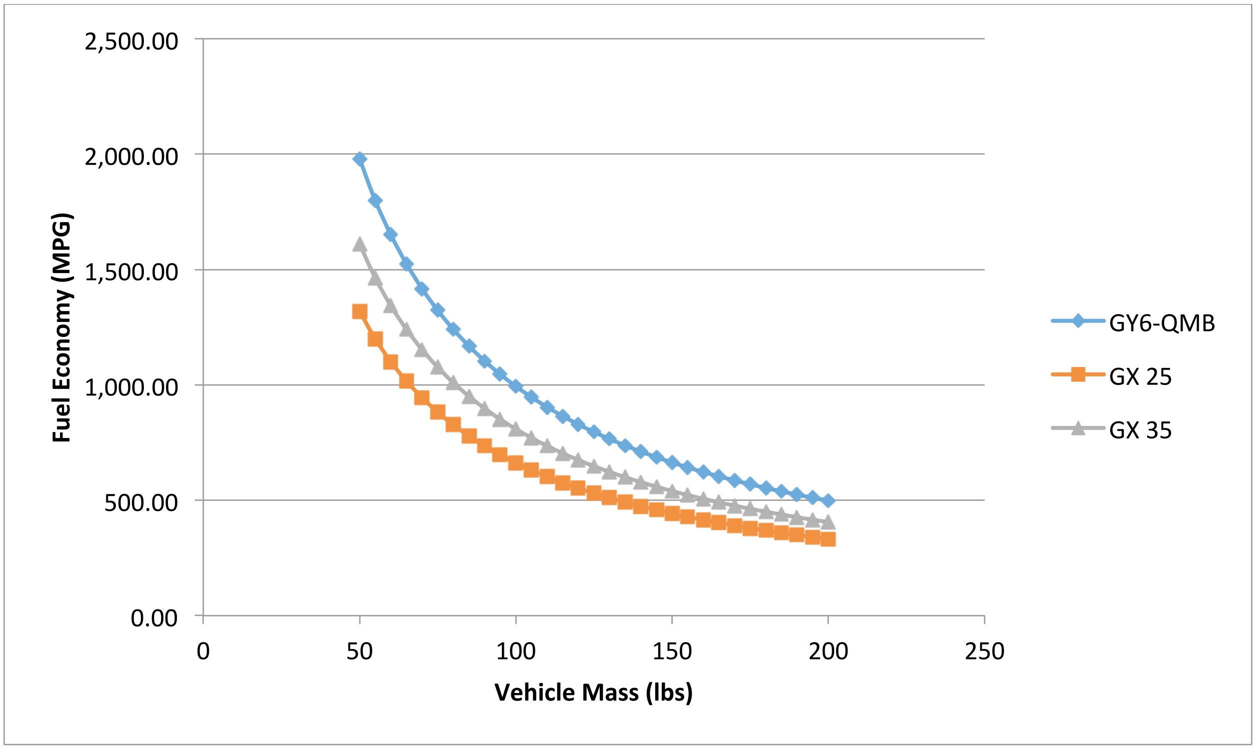


Figure 3.6: Fuel Efficiency Plot

3.4. Drivetrain System

First, our team had three drivetrain design ideas (CVT belt system, roller chain & sprocket, and the shaft & gearbox drivetrain). However, the best choice was the roller chain & sprocket system, because it had the lowest weight, highest simplicity and the lowest cost among our choices. Therefore, we choose the roller chain & sprocket to be our drivetrain. As for our selected engine, it has a torque of 3.1 N-m @ 5500 RPM, produces a 2.1 KW @ 6500 RPM and has a 2.8 HP @ 6500 RPM. We can get the torque of the engine @ 6500 RPM by using the following equation:

$$T = \frac{(HP)(33{,}000)}{(2\,\pi)(RPM)}$$

However, the units of the torque will be (lb-ft) as for the above equation. Therefore the torque at 6500 RPM is = 2.262 lb-ft = 3.067 N-m. The gear ratio can be calculated using the following equation:

$$Gear\ Ratio = \frac{\left(\frac{RPM}{60\frac{sec.}{min.}}\right)(Wheel\ Diameter\ (meter)*\pi)}{\left(wanted\ speed\left(\frac{meters}{sec.}\right)\right)}$$

Where:

Used RPM = 6500 RPM

Wheel Diameter = 20 in. = 0.508 m.

Wanted Speed = 17 mph = 7.6 m/s

Therefore, the gear ratio will be about 20:1, and this gear ratio is valid only if we used 20 in. back wheel for our vehicle for a speed of 17 mph. To calculate the torque output from the drivetrain to the rear wheel we used the following equation:

$$Gear\ Ratio = \frac{T_B}{T_A} = \frac{N_B}{N_A}$$

Where:

B = Output, A = Input

T_B = Output torque of the drivetrain

T_A = Input torque to the drivetrain

$\frac{N_B}{N_A}$ = Gear ratio

As we calculated the gear ratio, which is 20:1, and the input torque to the drivetrain "T_A" is = 2.262 lb-ft = 3.067 N-m. Now, we can get the output torque of the drivetrain "T_B" going to the rear wheel as following:

$$Gear\ Ratio = \frac{T_B}{T_A} = \frac{20}{1}$$

$$T_B = 20 * T_A = 20 * 2.262\ lb.ft = 45.24\ lb.ft = 61.34\ N.m$$

The first two gears in our drivetrain have a gear ratio of 4:1, where the two gears are connected to each other with a chain, and the second two gears have a gear ratio of 5:1. Therefore, the total gear ratio for our drivetrain came up to be 20:1. To check if our gear ratio 20:1 is good enough to give us a speed close to 17 mph, we can use the output torque, $T_B = 45.24\ lb.ft = 61.34\ N.m$, to get the RMP at this torque,$RPM = \frac{(HP)(33{,}000)}{(2\,\pi)(T)} = 325.1$, and then use the following equation to get to the velocity of our vehicle:

$$V = (RPM) * \frac{(Wheel\ Diameter\ (meter) * \pi)}{60\left(\frac{sec.}{min.}\right)}$$

Therefore the velocity of our vehicle calculated to be about 8.65 m/s = 19.35mph, which is close enough to our assumed needed velocity of our vehicle. Furthermore, we made a secondary drive shaft in order to deliver our calculated gear ratio, which is 20:1 reduction. The shaft coming out from the engine is connected with a centrifugal clutch with 10 teeth sprocket. The secondary shaft had two sprockets, the first sprocket is a 40 numbers of teeth and the second sprocket is a 9 numbers of teeth. And the secondary drive shaft is about 4 in. in length which is supported with two bearings at the end of it. And the rear wheel is connected with a sprocket that has 45 teeth. As for the diameter of the secondary shaft, we used the following equation in order to get the diameter, saying that our highest RMP coming from the engine is about 4000 RPM, and our shaft will have a RPM of 1000, assuming that the shaft is made of AISI 1566 steel:

$$V = \frac{N\,P\,n}{12}$$

Where:

$V = Sproket's\ Velocity$

$N = Number\ of\ Sprocket's\ Teeth$

$P = Chain\ Pitch$

$n = Sproket's\ Speed, RPM$

$$d = \left[\frac{16\,n}{\pi}\left(\frac{\left[4\left(k_f\ M_a\right)^2\right]^{1/2}}{S_e} + \frac{\left[3\left(k_{fs}\ T_m\right)^2\right]^{1/2}}{S_{ut}}\right)\right]^{1/3}$$

Where:

$d = Shaft\ Diameter$

$n = Factor\ of\ Safety$

$S_e = Endurance\ Limit$

$S_{ut} = Tensil\ Strength$

$k_f = Fatigue\ Stress - Concentration\ Factor\ for\ Bending$

$k_{fs} = Fatigue\ Stress - Concentration\ Factor\ for\ Torsion$

$T_m = Midrange\ Torque$

$M_a = Alternating\ bending\ Moments$

After applying the previous equations and using the assumption for the calculation, our secondary shaft had a diameter of about 0.75 in. Therefore our final shaft design will look like figure 3.7, which is an image generated via SolidWorks.

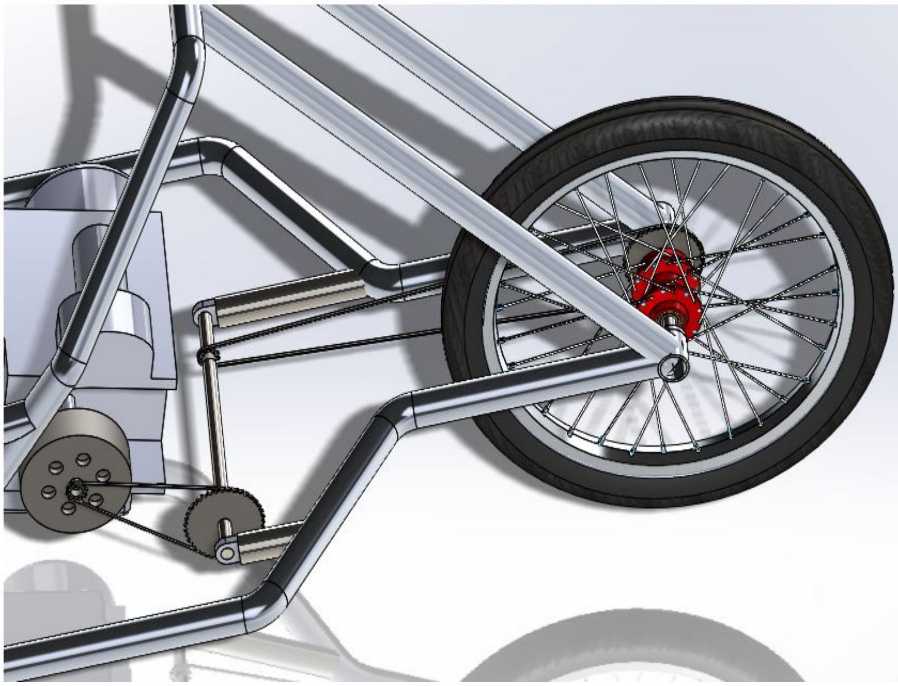
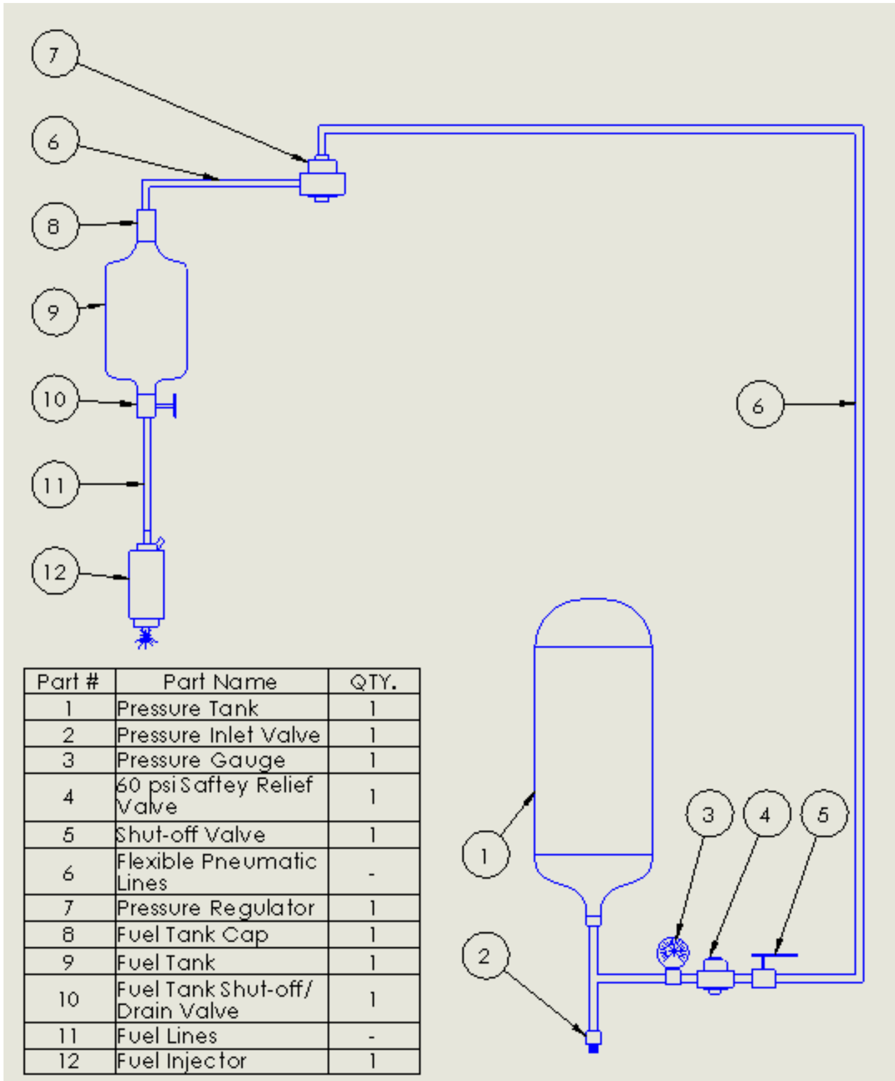


Figure 3.7: Drivetrain Design

3.5. Fuel System

The fuel system for the prototype had to be designed within the constraints laid out by the Shell Eco-marathon rules and regulations. With the constraints in mind, the team designed a fuel system that would use a compressed air in place of the electronic fuel pump that could not be used. The design consists of a large plastic 2-liter bottle that serves the purpose as a pressure vessel. The pressure vessel is attached to a brass fitting assembly which serves several functions. Compressed air will be added to the pressure vessel through a Schrader valve to just under 60 psi. There is a 60 psi pop-off pressure relief valve that maintains a safe operating pressure so that the pressure inside the glass fuel tank never exceeds 72 psi. There is also a series of pressure gauges and pressure regulator that allows pressure to fill the tank at an adjustable rate. There is also a shut off valve that can be closed to isolate the pressure vessel and fuel tank. Figure 3.8 shows a schematic of the fuel system designed.



Part #	Part Name	QTY.
1	Pressure Tank	1
2	Pressure Inlet Valve	1
3	Pressure Gauge	1
4	60 psi Saftey Relief Valve	1
5	Shut-off Valve	1
6	Flexible Pneumatic Lines	-
7	Pressure Regulator	1
8	Fuel Tank Cap	1
9	Fuel Tank	1
10	Fuel Tank Shut-off/ Drain Valve	1
11	Fuel Lines	-
12	Fuel Injector	1

Figure 3.8: Fuel System Schematic

3.6. Electrical System

The electrical system for the vehicle will be power by a small 12 volt lead-acid battery. Coming directly off of the battery will be the required external kill switch. This way the vehicle will not be operational until that kill switch is in the run position. The power is then passed to the starter relay which wires to the electric starter motor. Coming from the starter relay the internal kill switch, start button, and starter light are wired in series so that the vehicle will illuminate a 21W light when the starter is engaged. The internal kill switch is also wired to the key switch in the ECU that if not in the on position, the vehicle will not run. The vehicle is equipped with a horn that is controlled by a push button switch inside the car. It is directly connected to the battery so that in case of vehicle failure the driver will still be able to use the horn to signal for help. The vehicle also has a charging system that uses a voltage regulator and a stator to recharge the battery. The vehicle is equipped with a electronic controlled fuel injection system. This system has an ECU with several sensors, CDI output, and a performance switch that all work in conjunction to accurately take readings and output signals for the engine performance. These sensors include an O2 sensor to take oxygen readings from the exhaust, IAT sensor that measure intake air temperature, ECT sensor that measures the engine temperature, TPS that measures the throttle position, and a MAP sensor that measures the manifold absolute pressure. The ECU has a performance switch that switches between two profiles: ECO and RICH. For this competition the vehicle will be set on the ECO setting. The ECU also has a MIL lamp that illuminates when there is a problem with the fuel injection system. This acts much like a check engine light. The final thing that the ECU performs is sending an output signal to the CDI. This controls the spark of the spark plug of the engine. Figure 3.9 shows the general layout of the electrical system. Figure 3.10 shows the electrical schematic for the Ecotrons fuel injection kit.

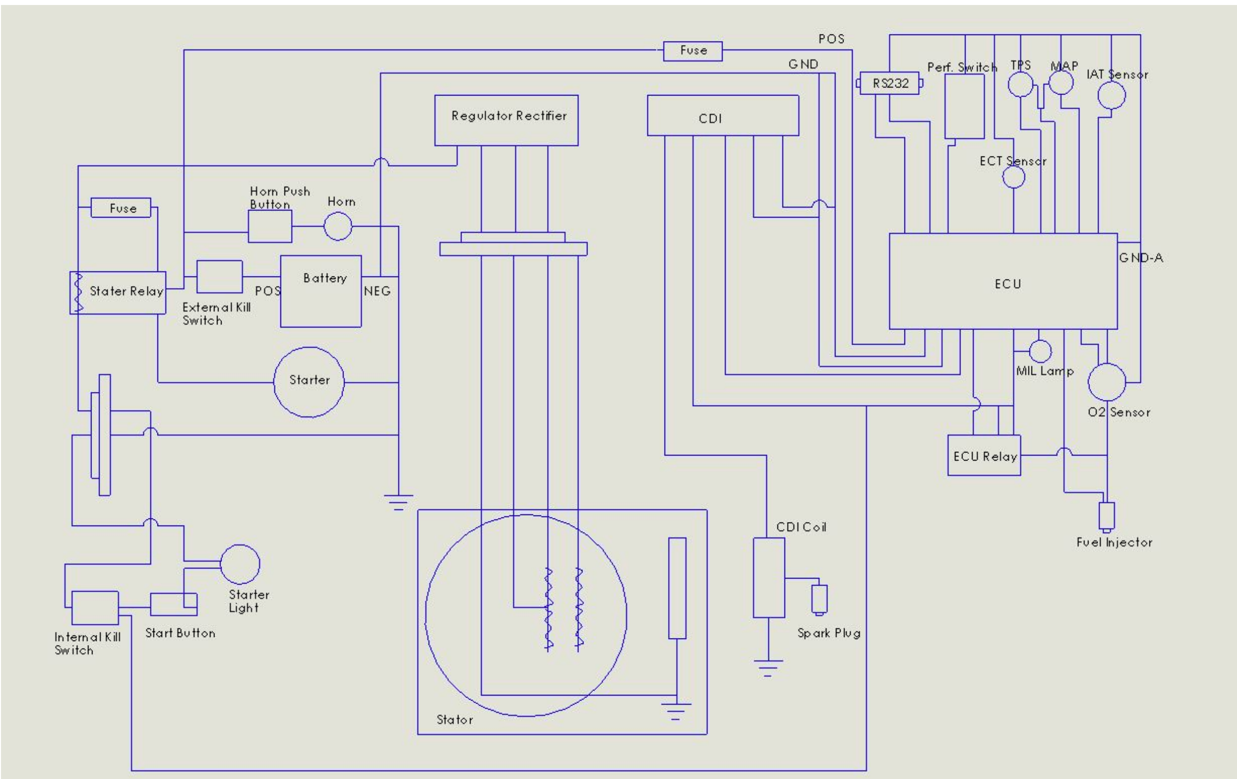


Figure 3.9: Electrical System Diagram

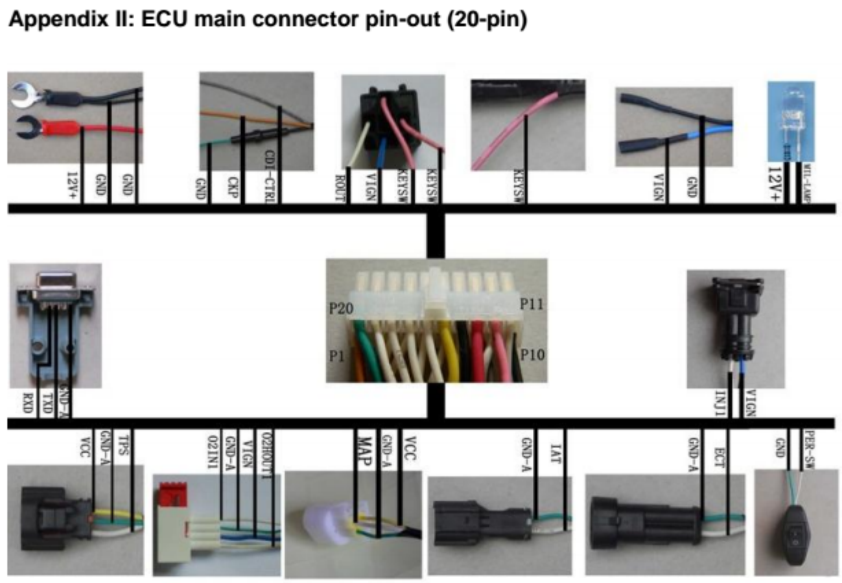


Figure 3.10: Ecotrons Circuit Diagram

4. Prototype Fabrication

4.1. Frame and Fairing

Frame

In design, the frame used different bends in the aluminum tubing to try and minimize the number of welds used. However, the aluminum used was very brittle due to the heat treatment, so many pieces had to be cut and welded into place from the initial design. Figure 4.1 shows the aluminum frame after welding.

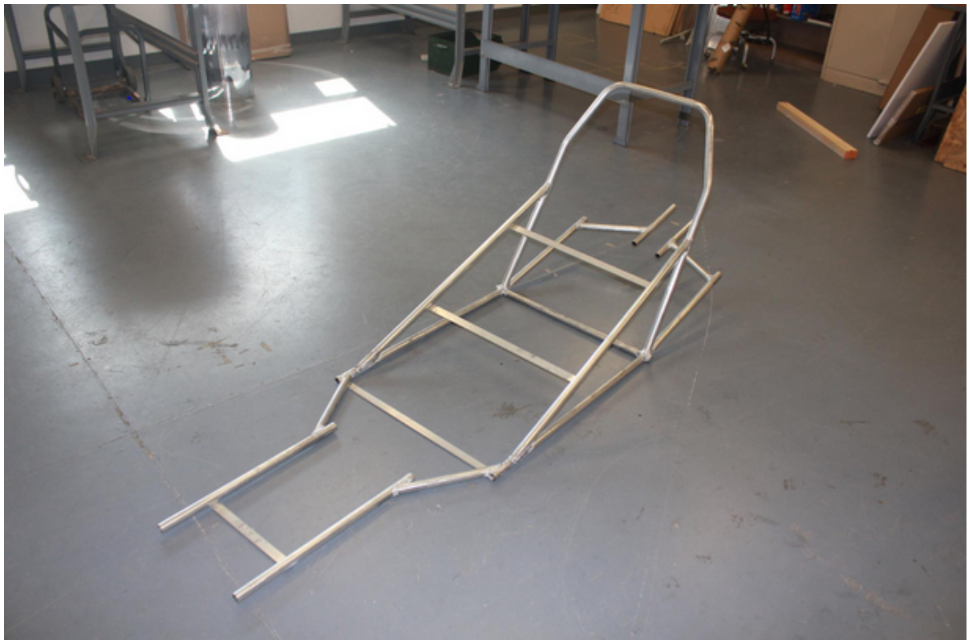


Figure 4.1: Fabricated Frame

The increased number of welds along the frame decreased the strength of the frame and the rigidity it was capable of holding. This was discovered once the rest of the vehicle components were installed and the frame was placed onto the ground. With a driver in place, the frame dragged on the ground, so additionally diagonal braces were added to improve rigidity. Carbon fiber panels with a Nomex honeycomb center were used as the floorboards as well as a firewall to separate the driver from the engine compartment. Figure 4.2 shows the frame with the panels installed as well as the other vehicle subsystems.

Figure 4.2: Assembled Frame

Fairing

The fairing was constructed using a spine and ribs made out of OSB. The spine and ribs were cut to a shape that was large enough to encompass the car at the critical positions, most notably the rollbar and the narrowing at the front wheels, this can be seen in figure 4.3. The rest of the shape was created as an attempt to make a smooth transition between the critical locations. After the basic shape was achieved using the OSB, screen was applied in the spaces in between the ribs so that the void wouldn't have to be completely filled. On the outside of the screen, plaster was applied to take up the large voids. The plaster was then sanded down to get a smoother surface. Body filler was applied to further smooth the surface of the plug. An initial coat of paint was applied to the body to make imperfections more noticeable. After that coat of paint more body filler was applied to fill the low spots. After the second coat of body filler, the plug was painted again.

Figure 4.3: Fairing with OSB Sections

The fairing is a composite of fiberglass and carbon fiber with thermoformed windows for visibility. There is an initial layer of fiberglass weave, two layers of a fiberglass veil and then a final layer of 10k carbon fiber weave. In order to be able to release the part from the mold later, mold release wax was applied to the plug followed by polyvinyl alcohol (PVA). These two items are common in the composites industry to release molds. The epoxy impregnated fabric was then laid up on top of the plug. The final layup can be seen in figure 4.4 before cutouts were made for the windows.

Figure 4.4: Laid-up Fairing

4.2. Steering, Wheels and Braking

Steering

The steering design problem was fixed by creating a new design that can withstand the force and the torque experienced by the driver. The new steering design was less complicated in comparison to the previous design. The idea of having the cross member placed on top of the frame remained the same with the uprights installed at the edges. The only difference that has been made was by creating two support steering columns that are located before and after the cross member. The first support steering column is attached to the carbon panels and supported with two members that are welded to the frame, as shown in figure 4.5. The steering rod will go through the support steering column all the way to the end of the vehicle. The second support steering column was attached to the frame at the end of the vehicle allowing the steering rod to go through it and stay secured. The actual steering column were the tie rods attached was flipped upside down so the driver can slide his foot to the end of the vehicle. Also, the steering arms were flipped upside down too to match the location of the steering column. This design eliminated the force and torque the steering rod was experiencing, and allowed for a clean turning operation. Also, the driver was experiencing slipping since the carbon panel's surface is so soft. By installing the second support steering column, the driver was able to rest the legs against the member eliminating the sliding motion experienced. Figure 4.5 is displaying the completed steering system attached to the vehicle.

Figure 4.5: Final Steering Design

Wheels

The wheels were maintained by replacing the bearing on the inner and outer sides of the wheels. This replacement allowed the wheels for a smoother rolling during testing as shown in Figure 4.6. Also, the tires were torn off during the testing period, therefore they had to be replaced with a newer tires.

Figure 4.6: New Inner and Outer Bearings

Brakes

The calipers, adapter mounts, and rotors were reused from the previous year vehicle. Brake cables and housing was purchased and mounted onto the frame throughout the vehicle. The cables attached to the brake levers on the steering wheel. The calipers were constantly being readjusted to eliminate rubbing on the rotors while still providing enough force to brake the car. Two brake lines connect the front brakes. Both lines needed to be activated by only one lever. A dual cable brake lever was used to control the front brakes instead of a brake splitter due to time constraints and manufacturing issues. A custom made mounting adapter was used for the rear brake to fit on to the rear dropouts.

4.3. Engine

The engine came shipped with a CVT attached. Since the design used a chain drive, the CVT was removed from the motor and the engine case was cut down to remove excess material. Figure 4.7 shows the engine as it was initially assembled, while Figure 4.8 shows the engine after the CVT was removed and the carburetion system removed also.

Figure 4.7: Complete GY6 Engine Assembly

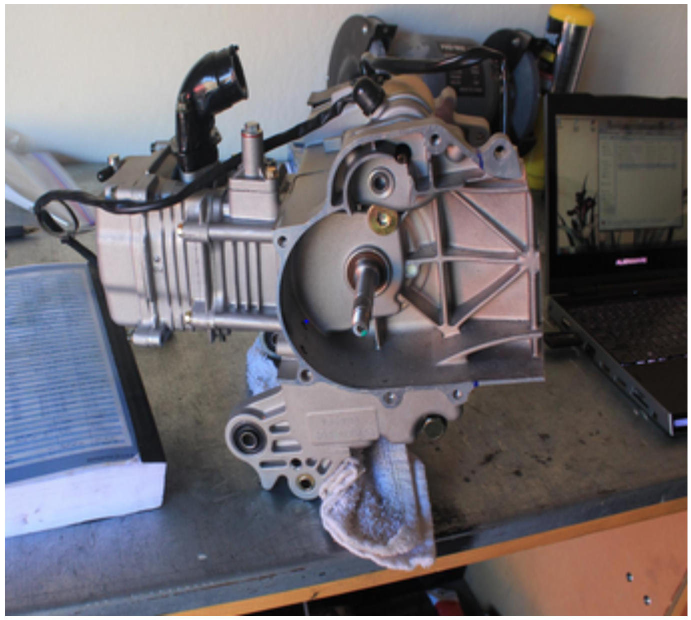


Figure 4.8: GY6 with CVT and Carburetor Removed

After the engine case was modified and the carburetor was removed, the EcoTrons fuel injection kit was installed. The engine was then placed onto a stand in the campus machine shop to be tested. Figure 4.9 shows the engine on the stand with the fuel injection kit installed.

Figure 4.9: Engine on Test Stand

The engine was then broken in on the stand before it was installed into the car. The engine was mounted using two front slotted mounts so that the engine could slide forward and used as a chain tensioner for the drivetrain. In addition to the front engine mounts, the engine was suspended from the frame using tie rods with Heim joints on the ends to allow for variations in angle. Figure 4.10 shows the engine mounted inside the car.

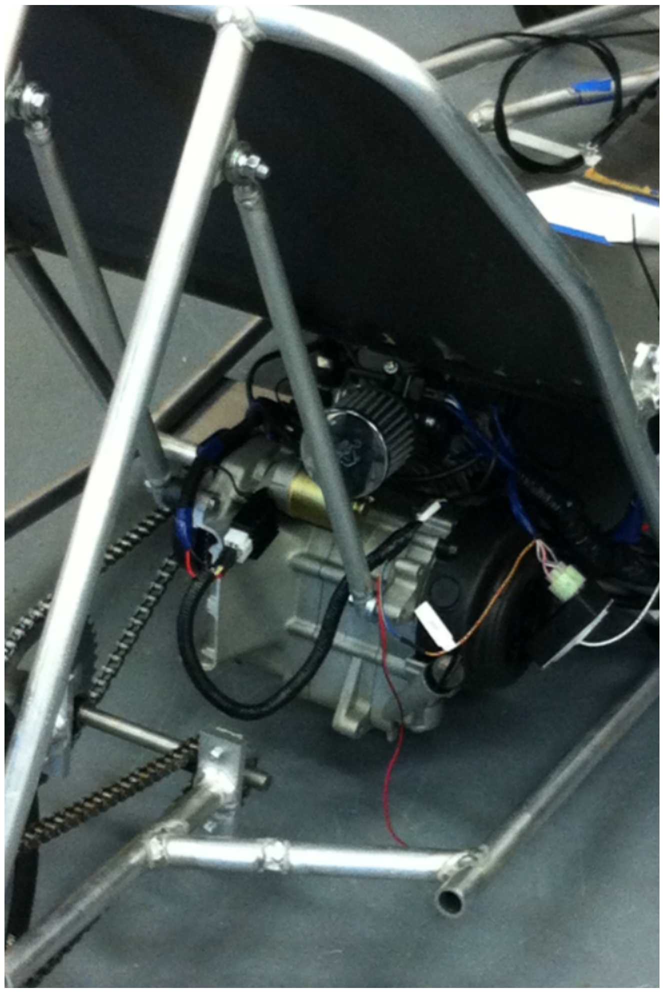


Figure 4.10: Engine Mounted In Car

4.4. Drivetrain

When we first tried to attach the centrifugal clutch to the output engine shaft, the clutch did not fit. Therefore, we machined a new shaft that threads to the output engine shaft, so we could attach the clutch to it. The centrifugal clutch has a 10 tooth sprocket which is connected to the 40 tooth sprocket in the secondary shaft using a chain. On the other end of the secondary shaft, we attached a 9 tooth sprocket to the secondary shaft, which is connected to the 45 tooth sprocket using a chain. The 45 tooth sprocket was attached to the rear wheel. The secondary shaft was connected to the frame by attaching the two bearings with pillow blocks at the end of the shaft to two aluminum plates. The two aluminum plates were welded to exposed tube ends of the frame. In order to reduce the drivetrain weight, the large sprockets were windowed. We machined a keyway in the secondary shaft in order to hold the sprockets in place.

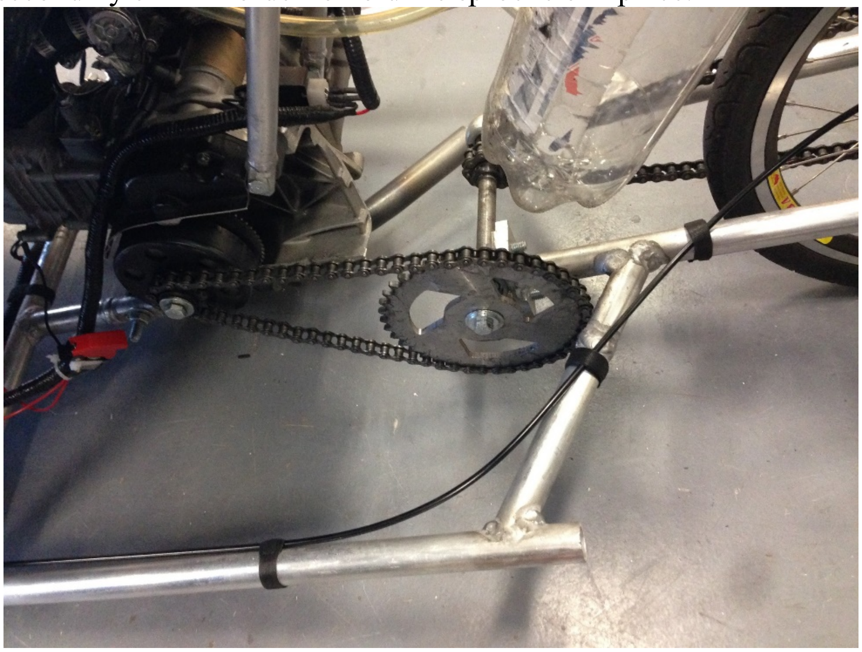


Figure 4.11: Drivetrain (Left View)

Figure 4.12: Drivetrain (Right View)

4.5. Fuel System

Using the proposed fuel system design, the team fabricated the fuel system using common brass knuckles fittings. These brass fittings include ¼" brass tees, 60 psi pop-off pressure relief valve, ¼" brass nipples, and a brass tubing adapter. The tubing used to connect the brass assembly to the fuel tank was a reinforced 5/16" (inside diameter) tube. The pressure vessel came from a 2-liter RC Cola bottle threaded into a brass garden hose adapter. The garden hose adapter was a part of the brass assembly. The pressure regulator and pressure gauges came from air compressor replacement parts. A nylon barbed fitting was pressed and epoxied into the fuel cap through a drilled hole. This barbed fitting allowed for the air pressure inside the pressure vessel to flow through the brass assembly and tubing to pressurize the fuel tank. Once the fuel tank was pressurized, the shut-off valve below the fuel tank allowed for pressurized fuel to reach the fuel injector. The system was pressurized to 2.5 bar, which is the appropriate pressure for the fuel injection kit. See Figure 4.13 for a picture of the fuel system.

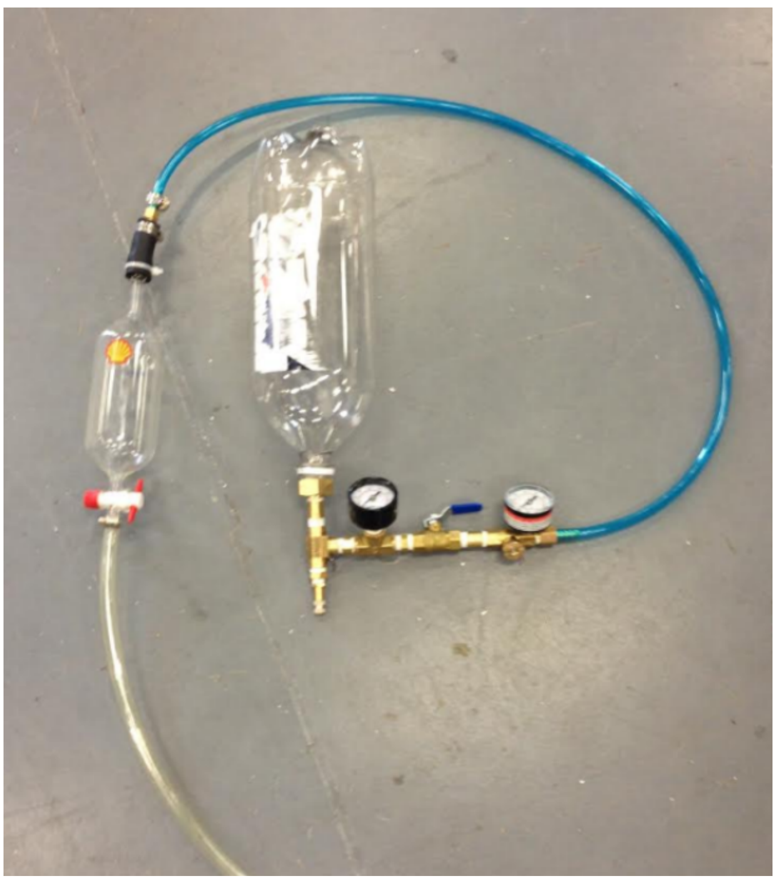


Figure 4.13: Fuel System

5. Testing and Results

A drivable vehicle, except for the fairing, was ready for testing by April 4th. Tests were performed on the streets around the machine shop and in the nearby parking lots. Tests were completed to estimate fuel economy, as well as check for the durability of design components. Table 5.1 shows the testing parameters.

Table 5.1: Testing Parameters

Driver Weight	178 lbs
Elevation	7000 ft above sea level (Flagstaff)
Fuel Consumed	100 ml
Course	0.2 mi laps with altitude changes

Testing trials showed many areas that needed to be slightly considered, most commonly involving hardware shaking loose. Lock nuts and Loctite was used in order to anchor the hardware in place. Testing also produced the first fuel economy estimates for the vehicle, with mileage ranges from 77 to 114 mpg; significantly lower than the estimated fuel economy. Changes were made to the engine tune in an effort to try and lean out the motor, but it continued to produce poor fuel economy.

While at competition, the team faced many setbacks. The engine failed to start consistently, and had a difficult time continuing to run during and after warm up periods. This was mostly due to the fuel economy profiles, and the incorrect selection of the fuel profile mode. Once the error with the fuel switch was discovered, the car started more reliably, but it was too late to make any substantial modifications to the tune in order to maximize the fuel efficiency and reliability of the engine.

Additionally, the aluminum steering cross member failed, as shown in figure 5.1.

Figure 5.1: Aluminum Cross Member Failure

In order to continue to compete at the competition, the team replaced the aluminum cross member using parts that were available: a 2x4 wooden cross member from the vehicle packing crate. Figure 5.2 shows the wooden cross member in the vehicle.

Figure 5.2: Wooden Steering Cross Member

While testing the new wooden cross member, the fuel tank required by Shell broke during refueling. A new tank was purchased the next morning. In addition to the problems with the fuel tank, the fuel cap was a source of constant problems. Shell rules state that the cap provided with the tank must be used, and if a pressure bottle is fitted, it needs to be adapted to the fuel cap. The cap was made of a Pyrex material, which is very brittle, so adapting a barbed fitting for the air hose to fit into the tank either broke the cap or would leak constantly. A plastic barbed fitting with silicone sealant worked, but it was only implemented during competition.

The vehicle passed technical and safety inspections even after the cross member was replaced with wood, but the vehicle had a difficult time starting at the line for an official run. After several minutes, the vehicle was able to start and slowly leave the line, but it did not complete a full lap. After taking the car back into the paddock area, the vehicle would not start at all, which was traced to a blown fuse for the starter relay. Once the fuse was replaced, the car started again and was lined up to attempt a second official run. This time, the vehicle still did not complete a full lap, resulting a DNF (did not finish) for the NAU Eco Marathon Team with no official results for fuel economy.

6. Cost Analysis

The project had an initial budget of $2,500 as supplied by SAE of NAU. The team received approximately $900 through donations from private parties. Table 6.1 shows the breakdown of costs for the project.

Table 6.1: Tabulated Vehicle Cost

System	Cost
Engine	$909
Drivetrain	$190
Electrical	$78
Frame	$134
Fairing	$350
Braking	$290
Steering	$90
Wheels	$537
Hardware	$95
Safety	$516
Total	**$3,189**

7. Conclusions

The NAU Eco-marathon team designed and built a car with a goal of maximizing vehicle fuel economy. The frame was made from aluminum to save weight and cost, while stiffened with carbon fiber panels with a Nomex honeycomb core. The engine selected was a Honda GY6-QMB 50cc and was picked because of its high compression ratio and presence of electric start. EcoTrons fuel injection was added to the motor to improve its efficiency and maximize the fuel economy capabilities. The wheels, tires, and brakes were off-the-shelf bicycle components. The steering system was a Pitman arm setup with a quick ratio. The expected fuel economy based on the BSFC figures was around 800 miles per gallon.

In testing and competition, the vehicle did not perform up to expectations. Due to issues with the engine tune, the best fuel economy observed by the team was 114 mpg driving around outside of the machine shop. At competition, the vehicle experienced a catastrophic failure to the front steering cross member that had to be repaired with the only available material: wood from the packing crate. Despite the numerous reliability challenges, the team persevered and was able to have a car pass the technical and safety inspections. Despite passing inspections, the car was not able to complete a run at the competition and the official result for the team was a DNF.

NAU could be a serious competitor in future Eco Marathon competitions by following some of the lessons learned from this team's experience, as well as observing other schools at the competition. Most schools who participated used a composite monocoque chassis design that could be used for many years. This allows the vehicle to have a strong, rigid, aerodynamic, and lightweight body that can be reused, so following design teams can focus on single aspects of the vehicle, such as the engine. The intermediate drive shaft was a constant source of alignment issues, so a single reduction would be a better design choice. Using quick release fittings for the fuel and air lines would make filling up the fuel easier and helps to avoid breaking the fuel tank. The wheel sizes used were an off-size for a bicycle, resulting in extended time fitting a hub and difficulty in finding tires and tubes. If standard wheel sizes are used, tires and tubes would be easier to find.

The largest area for improvement is with the engine. A 50cc engine is larger and more powerful than it needs to be for a competition like this. Most teams used engines 35cc or smaller. If fuel injection is used, a wideband O2 sensor should be used instead of a narrow-band sensor to allow for more precise tuning of the engine. A narrow band sensor can only tell if the engine is running rich or lean, not how rich or how lean. Using a wideband O2 sensor can allow for a more precise tune on the engine, provided there is adequate tuning time.

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