(Form 6)

Vehicle Description Form

Updated 12/3/13

Human Powered Vehicle Challenge

Competition Location: University of Central Florida

Competition Date: April 11-13, 2014

http://go.asme.org/HPVC

This required document for all teams is to be incorporated in to your Design Report. Please Observe Your Due Dates; see the ASME HPVC for due dates.

Vehicle Description

School name: Olin College of Engineering

Vehicle name: Cheryl

Vehicle number 4

Vehicle configuration

Upright ______ Semi-recumbent X

Prone ______ Other (specify) ______

Frame material Steel-Carbon Fiber Monocoque

Fairing material(s) Carbon Fiber

Number of wheels 3

Vehicle Dimensions *(please use in, in^3, lbf)*

Length 93.9in Width 21.3in

Height 36.4in Wheelbase 52.7in

Weight Distribution Front 60%* Rear 40%* Total Weight TBD*

Wheel Size Front 16in Rear 20in

Frontal area 682in^2

Steering Front X Rear ______

Braking Front X Rear ______ Both ______

Estimated Cd 0.185

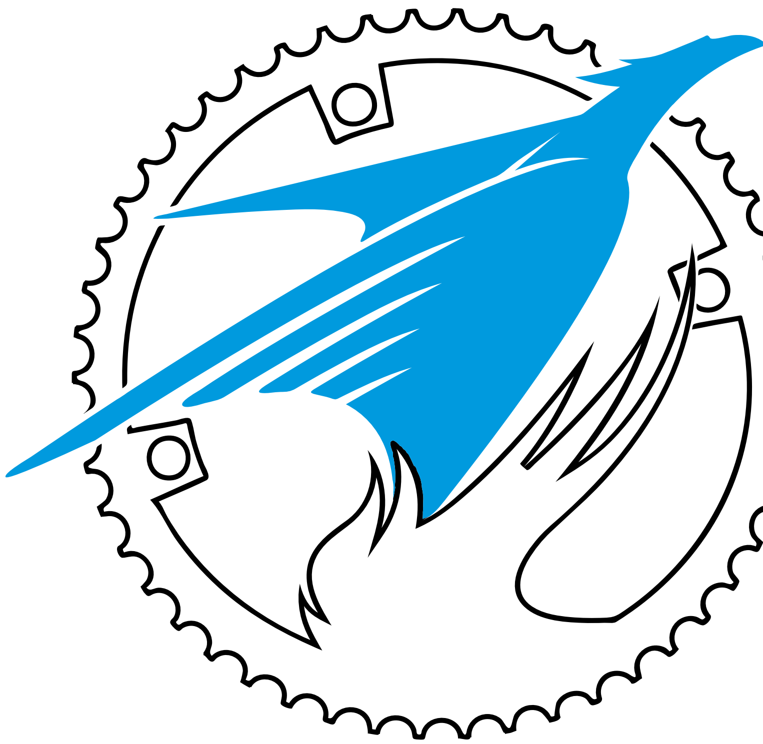
Vehicle history (e.g., has it competed before? where? when?) *Cheryl* was designed exclusively for the 2014 ASME HPV Challenge and has not yet competed.

* Vehicle has not been completed, weight distribution estimated.

** Expected weight is 72lbf.

Olin College OF ENGINEERING **Human Powered Vehicles**

2013 - 2014 Design Report



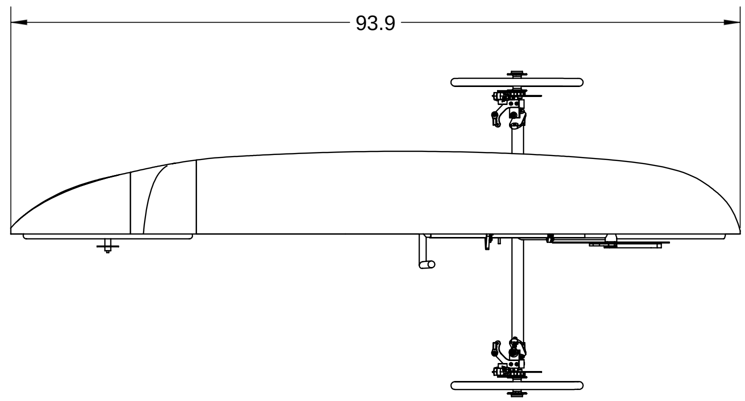
Cheryl

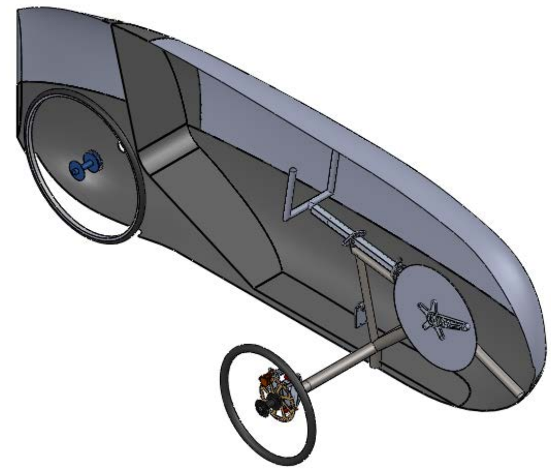
Vehicle #4

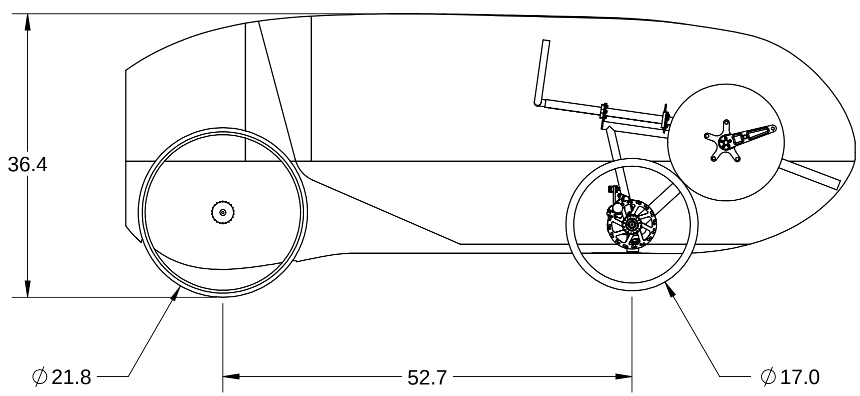
Alex Spies
Anne LoVerso
Ben Chapman
Cullen Ross
David Pudlo
Dennis Chen
Gaby Waldman-Fried
Halley Pollock-Muskin
Ingrid Hagen-Keith
Jackie Rose
Janie Harari
Jay Patterson
Jeff Holzgrafe
Jennifer Wei
Jessica Sutantio
Josh Sapers
Kari Bender
Kristyn Walker
Madeleine Fort
Maggie Su
Mary Ruthven
Meghan Tighe
Michael Searing
Mike Warner
Morgan Bassford
Nagy Hakim
Nick Eyre
Sarah Walters
Shrinidhi Thirumalai
Tatiana Anthony

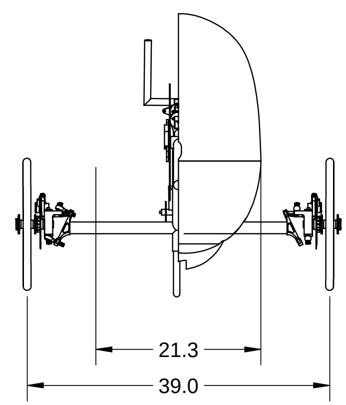
Faculty Advisors:
Aaron Hoover & Christopher Lee

hpv@olin.edu http://hpv.olin.edu









UNLESS OTHERWISE SPECIFIED:

DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994.		PERPENDICULARITY:	0.001" / INCH
DIMENSIONS ARE IN INCHES.		CONCENTRICITY:	0.002" T.I.R.
DE-BURR AND BREAK ALL SHARP EDGES .003 MIN.		PARALLELISM:	// 0.001" / INCH
TOLERANCES ARE:	X.XX = ±0.01 X.XXX = ±0.005 X.XXXX= ±0.001 ANGLES: ±0.5°	FLATNESS:	0.001" / INCH
		ROUGHNESS:	125

THIS DRAWING IS THE SOLE PROPERTY OF THE FRANKLIN W. OLIN COLLEGE OF ENGINEERING HUMAN POWERED VEHICLE DESIGN TEAM. DO NOT DUPLICATE WITHOUT PERMISSION

	APPROVED	DATE
ENGINEER	TEAM	3/7/2014
DRAWN	N. EYRE	3/7/2014
CHECKED	TEAM	3/7/2014

Olin College of Engineering
Human Powered Vehicles

Cheryl

2014 COMPETITION VEHICLE

SIZE	PART NO.	REV
B	OLIN-HPV2014	-

SCALE 1:16 | DO NOT SCALE PRINT | SHEET 1 OF 1

Abstract

For its ninth year, the Olin College Human Powered Vehicle Team will return to the ASME HPVC, this time with our new vehicle, *Cheryl* . The team's goals for this year are to construct a practical, comfortable, and reliable vehicle for all weather conditions while maintaining efficiency and speed. Following the team's long standing tradition, the vehicle will be built to accommodate all team members.

Our performance at the 2013 competition led us to focus on the following areas in our design:

1. *Cheryl* will be a reliable vehicle, allowing the rider to ride confidently without fear of vehicular failure. Unlike our previous competition vehicle *The Plaid Panther*, *Cheryl* will be built simply, with less focus on weight and size reductions. Instead of optimizing solely for speed, the team will also maintain a higher factor of safety through our systems.
2. *Cheryl* is a tricycle, unlike any vehicle the team has previously brought to competition, leading to a more stable vehicle than ever before. This additional stability will be advantageous in endurance race obstacles and makes *Cheryl* more accessible for riders of varying abilities.
3. *Cheryl* is an all-weather vehicle, designed to optimize safety and control in a variety of climate conditions. The fully enclosed fairing with air ducts offers breathable protection from the elements. The easily removable front wheels allow for the potential to replace them with skis or ice skates. These traits create a practical recumbent vehicle for year-round use in New England weather.
4. *Cheryl's* additional stability and reliability dramatically improve the safety of the vehicle in comparison to past entries. Furthermore, a redesigned rollover protection system improves rider safety during significant crashes.

Contents

Part I
Design

1 Objective

For the 2013-2014 season, the Franklin W. Olin College of Engineering Human Powered Vehicles team set out with the goal of exploring and innovating in the field of human powered vehicles through the design, analysis and construction of our vehicle, *Cheryl*. *Cheryl* was designed to be a practical, reliable and high-performance vehicle suitable for transportation or recreation. Our goals of reliability and practicality were major guides in our design process.

2 Background

Global climate change and the increasing cost of fossil fuels have inspired communities worldwide to invest in more environmentally friendly forms of transportation. While bicycles are convenient and economical, they lack the safety features and speed offered by modern automobiles. Faired recumbents offer increased rider protection and power efficiency unparalleled by traditional bicycles, supplying yet another alternative to modern automobiles.

3 Prior Work & Background Research

As the team's ninth competition vehicle, *Cheryl* takes inspiration from several of our prior designs, most notably *The Plaid Panther* (2013) and *Seabagel* (2012). The custom cranks and crankshaft combine the best features from both of the past two vehicles' custom cranks to reduce slop while maintaining a lightweight and narrow design. The manufacturing process used to build *Cheryl's* aerodynamic fairing is the third iteration of the process previously used on *Seabagel* and *The Plaid Panther*. Finally, the design of the steel to carbon interface plates present on *Cheryl* has remained largely unchanged since their first introduction in *Seabagel*.

Cheryl represents the team's first exploration into recumbent tricycles. As such, research was performed to investigate past work in the field. Most notable was the use of the Rickey Horwitz Design Primer[1] which was used heavily in the design of the front wheel configuration. Furthermore, in the design of the drivetrain, we utilized component friction data from Friction Facts[2].

4 Organizational Timeline

Cheryl was constructed entirely in the spring 2014 semester by the Olin Human Powered Vehicles Team. In the fall, the team constructed two prototype vehicles: a leaning tricycle and a monowheel. Design of *Cheryl* began on January 22 and had a design review on February 7 to solicit feedback from the Olin community. February was primarily devoted to the construction of a prototype vehicle and the refinement of the steering design.

Meanwhile, a separate team prepared the fairing mold plug. In March, the competition vehicle is to be constructed in time for April's competition. Tasks completed in the spring 2014 semester were completed in two week time periods. Halfway through each task period, progress was evaluated. When necessary, rescheduling or restructuring was implemented. At the end of each two week task period, a deliverable was presented and report was written before moving on.

5 Vehicle Configuration

Each of the team's eight previous vehicles has been a faired recumbent bicycle. The team's development efforts have historically focused on optimizing vehicle quality, efficiency and durability. While aerodynamic and streamlined, recumbents are inherently unstable, especially at low speeds, due to their low center of mass. The previous vehicle, *The Plaid Panther*, met the goal of improved aerodynamics and weight but was difficult to ride and too small to comfortably fit all team members.

	Stability	Weight	Manufacturability	Manueverability	Ease of Use	Aerodynamics	Innovation	**Total**
Weighting Factor	6	4	4	8	8	8	4	
Upright Bicycle	4	4	4	8	8	0	0	67%
Recumbent Bicycle	3	3	4	4	4	8	2	67%
Leaning Tricycle	3	0	2	0	4	4	4	40%
Tadpole Tricycle	6	2	1	8	8	6	3	82%
Conventional Tricycle	6	1	2	4	8	4	1	62%
Monowheel	0	1	3	0	0	0	4	19%

Figure 1: Vehicle Configuration Design Matrix

Cheryl is a radical departure from our team's previous vehicles and was designed specifically for the 2014 ASME HPVC. Each of the vehicle's subsystems has been reimagined from the ground up in order to create a more practical, effective, and competitive vehicle. The vehicle's components can be divided up into the steering, drivetrain, aerodynamic fairing, and structure.

In the design of *Cheryl*, the team prioritized ease of use, stability, and maneuverability to improve the vehicle's performance in riding environments more common than the drag races for which *The Plaid Panther* was optimized. A weighted analysis of these considerations drove the team to design and build a recumbent tadpole tricycle (Figure 1). *Cheryl* combines the utility and convenience of an automobile with efficiency far superior to that of an upright bicycle to create a fast and practical everyday vehicle.

6 Structure

Cheryl is built as a ribbed carbon fiber monocoque shell with steel sub-frames. Ribs constructed of carbon-covered foam, are shown in Figure 2. Steel nut plates placed on ribs in the carbon monocoque serve as attachment points for the welded sub-frames. A thick reinforced carbon rollover protection system protects the rider in case of a crash.

All drivetrain and steering components mount to the modular front sub-frame (Figure 6). The welded steel frame is removable for maintenance and replaceable in case of failure. The driven rear wheel is independently supported on each side by steel plates attached to the monocoque.

7 Front Wheel Geometry

A tricycle is only as good as its steering. Our goals for the steering mechanism were to minimize frontal area, permit adjustability to compensate for varying rider heights and enable smooth ingress and egress while maximizing manufacturability.

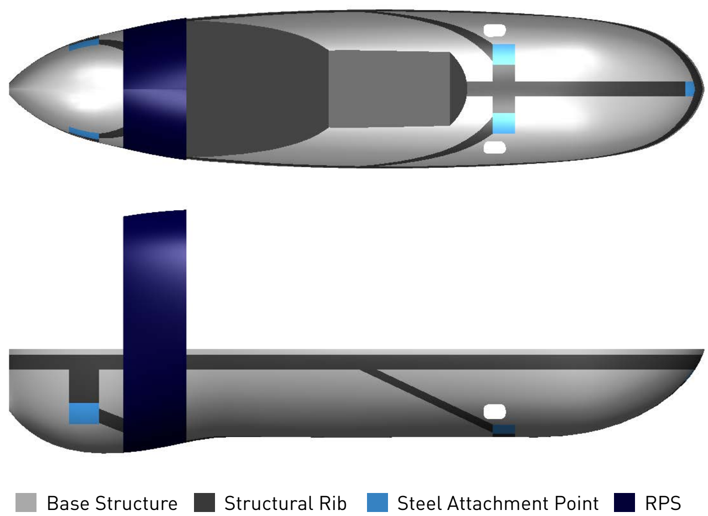


Figure 2: Monocoque Structural Rib Configuration

7.1 Knuckles

Cheryl's knuckles serve as the connection points between the vehicle and its rear wheels (Figure 3). The machined 6061-T6 aluminum knuckles pivot on two spherical rod end bearings connected to a fixed knuckle mount block clamped into the end of the frame. The rod end bearings allow for adjustable camber while ensuring that the pivot axis intersects the wheel contact patch. Caster angle is adjusted by rotating the knuckle mount block in the frame tube. The wheel sits on a cantilevered shaft and is axially held on place with a retaining screw. A disk brake caliper is attached to each knuckle with an auxiliary mount plate. Finally, an adjustable plate connects the wheels to the steering control rods.

The knuckles were designed with manufacturability and precision in mind. A machined aluminum part was chosen over welded or bent sheet metal for increased precision in manufacturing. The knuckle mount block was also machined, allowing for the king pin inclination to be set on precise mill and not be affected by jigging or warping during frame welding. Furthermore, while the knuckle mount required CNC milling, the simple design of the main knuckle block allows for manual milling, with which a larger number of teammates are familiar with. Finally, the multi-part bolt-together knuckle ensures that all parts are symmetric across the vehicle.

7.2 Steering Control

The team began by considering several different steering options: over-the-seat, under-the-seat, direct knuckle and j-rod (push-pull). Although direct knuckle and under-the-seat are simpler than over-the-seat, they sacrifice frontal area and place the rider's hands close to the ground. Furthermore, over-the-seat is easily able to adjust for variations in rider

Figure 3: Knuckle Design

Figure 4: Telescoping Handlebar Linkage

size, leading us to eventually decide on over-the-seat steering for *Cheryl* .

The vehicle's handlebars are built as a steering column held in a telescoping bushing (Figure 4). The pin-locked sliding linkage allows for riders of all heights to ride.

7.3 Steering Linkage

Cheryl's handlebars are connected to the knuckles through a two-stage linkage. A tie-rod forms a four-bar linkage connecting the handlebars to a bell crank between the rider's legs (Figure 5). A second set of tie rods connect the bell-crank to the knuckles, achieving steering through Ackerman Compensation.

Figure 5: Steering Linkage Intermediate Link

8 Drivetrain

Cheryl is a rear-wheel drive vehicle. Given the vehicle's tadpole trike configuration and frontal steering, a rear wheel drive system reduces the need for a differential or actuated drive shafts. However, this may cause efficiency losses due to a longer chain.

The vehicle's chain passes under the rider from the pedals to the cassette and derailleur in the rear. Two sets of idler pulleys drop the chain below the seat. Each idler consists of a pair of plastic cogs on ball bearings.

Cheryl's drivetrain takes a drastically different form than predecessors *Seabagel* and *The Plaid Panther*. The linkage-mounted adjustable pedal systems of our past two vehicles have been replaced with a fixed-pedal configuration. While effective, the adjustable pedal systems added weight and dramatically increased the machined part count and the number of possible failure points. Although *Cheryl* lacks the adjustability of *The Plaid Panther's* rider variation compensation system, the loss is justified by a reduction in manufacturing, design, and maintenance time. Instead, rider adjustability will be accomplished by padding the back of the seat in the carbon monocoque.

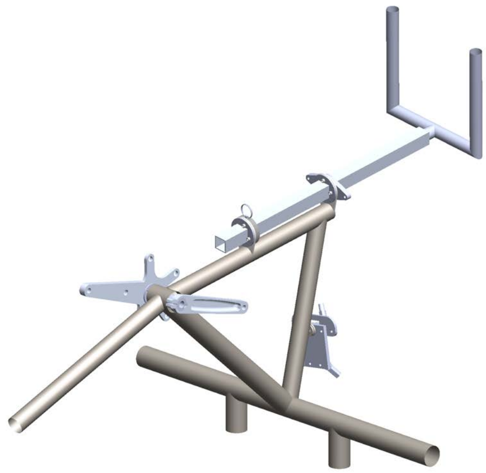


Figure 6: Front Frame, Steering & Drivetrain

The vehicle's cranks combine the aggressive weight production of *The Plaid Panther* with the slop-free clamp mechanism of *Seabagel*. Two 6061-T6 aluminum cranks were machined from billet and slide onto a 7075-T6 aluminum crankshaft. The crankshaft passes through a custom shortened bottom bracket containing standard bicycle cartridge bearings. The custom crank assembly allows for a dramatically reduced Q-factor over a conventional bicycle.

8.1 Gearing

On recent team vehicles, the chain has been routed through an interchange to increase the gear ratio in order to achieve higher speeds. *Cheryl* is a departure from these designs and features a single chain system with no interchange. The rear wheel features a 9 speed derailleur with an 11-34 cog range, allowing for a wide range of gear ratios. This means that to achieve optimal gear ratios, a very large front sprocket is necessary. The team intends to experiment with sprockets containing between 70 and 90 teeth, giving the vehicle a 90 rpm cadence top speed upwards of 35 mph.

Chain rings this large are not widely available, and the team opted to manufacture its own chain ring. Manufacturing custom own chain rings brings the freedom to make different sizes for the different situations *Cheryl* will encounter. For example, drag races merit a larger size sprocket whereas utility endurance racing and everyday commuting are better suited to smaller sprockets. The interchangeability of custom chain rings at competition will be used as an advantage. Additionally, there are many benefits to a single-chain configuration including reduced weight, increased efficiency and ease of chain alignment.

9 Aerodynamic Fairing

The goal of maintaining an aerodynamic shape of *Cheryl* drove the creation of a streamlined main body with outlying wheel pods to reduce drag. Design began with a simulation-driven comparison between an all-encompassing fairing and a central fairing with outboard wheels. Initial simulation that the all-encompassing fairing design had a slight aerodynamic advantage to. However, splash resistance, increased manufacturability, and weight concerns drove the decision to pursue a central fairing with outboard wheels.

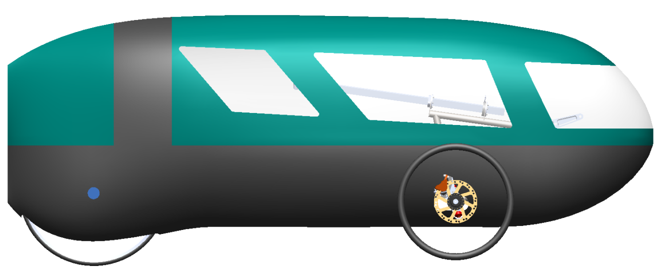


Figure 7: Vehicle Windows

Cheryl is a wider vehicle than past entry *The Plaid Panther*, providing additional rider comfort and increased pedaling room. To balance this increase in frontal area, the vehicle has a super-reclined rider position (25° from horizontal). Though the frontal area is increased by the wider central fairing and the tricycle wheels, this year's design improves visibility and increases rider confidence with panoramic windows around the rider (Figure 7).

Cheryl is the team's shortest vehicle in the past four years. Instead of last year's 8' 6" length, *Cheryl* is only 7' 10" long; this assists maneuverability, manufacturability and weight. Though this length minimization decreased aerodynamic efficiency, the benefits were still deemed worthwhile.

Last year's fairing design included a 'head bubble' which allowed for high visibility in both the forward and peripheral directions. This year's super-reclined rider position requires a different window approach. *Cheryl's* windows are located both directly in front of the fairing and also on the side to allow for a panoramic view of the road.

9.1 Rollover Protection System

Cheryl contains the team's third iteration of the integrated composite fairing-rollover protection system (RPS) introduced in *Seabagel*. The past two years, the RPS has consisted of a hoop of carbon fiber with a wide foam rib covered by a layer of Kevlar. The carbon and geometry provided the necessary stiffness to this design, and the Kevlar protected the rider from the irritation of the carbon and brittle fracture in case of catastrophic failure. However, its open loop form factor required steel tube bracing to prevent outward bowing and meet the competition standards. Instead of repeating this weighty method, *Cheryl's* seat back is integrated into the vehicle's rollover protection system. With a continuous wall of composite material across the rear of the RPS, this design will provide a significant increase in strength and isolate the rider from the rear wheel compartment. Aramid fabrics will be applied over the carbon fiber for rider protection.

9.2 Mold Design

Producing *Cheryl's* fairing required the production of a mold followed by the creation of the monocoque body and forward hatch.

The 2014 fairing molds, shown in Figure 8, were made in three parts (bottom half, top front and top rear) from a two-part CNC-routed male foam plug. Each mold section, constructed of an inner layer of fiberglass under carbon basalt and several wide ribs, has a four inch lip to allow cavity vacuum bagging rather than needing to wrap the entire mold. Cavity vacuuming has reduced labor and cost for each lay-up. This process has resolved several issues regarding vacuum seal in past years.

In past years, machining of a single male plug took many hours; this year, the two halves of the plug were built separately (the top part of the fairing and the bottom), increasing process efficiency. Two inch thick pieces of foam were machined in horizontal rather than vertical slices, utilizing the full 4'x4' machining area of the router. The slice orientation consisted of a front slice and rear slice to get the full contour of the fairing. Total machining time was cut from 24 to 10 hours and the two-part design allowed a more accurate joining method.

Last year, a torsional twist was present in the male plug due to the two inserted steel tubes deforming helically. The new two-part plug provided flat surfaces, improving accuracy of alignment. The flat plug also allowed the mold to be created on a flat surface, creating more planar flanges for better alignment and vacuum sealing. Finally, splitting the plug in two has allowed for distribution of work as more people can work on the molds at any one time.

In addition to mold difficulties, once *The Plaid Panther's* carbon halves were made, the chosen joining method was heavy and inaccurate. The new three part mold allows for full coverage of the fairing during joining lay-ups, allowing for vacuum use at all stages in the manufacturing process.

Finally, care was taken to ensure a better surface finish on *Cheryl's* fairing than on past fairings. Last year's packing tape mold release saved time but created a ridged surface and was eschewed in favor of a return to a wax and polyvinyl alcohol (PVA) release. This method has dramatically improved the surface quality and overall appearance of *Cheryl*.

Figure 8: Cheryl's 3 Piece Fairing Mold

9.3 Carbon Monocoque

The main body of the fairing consists of a bottom shell and the rear rollover protection system. The two components will be created separately and combined to form a strong and rigid body. The outermost layer will be one layer of 6K HS weave followed by a layer of 2K Twill weave. Foam ribs covered in strips of 6K HS weave will be incorporated for added rigidity. The top-rear and bottom halves will then be joined at the lip around their shared edge while the rollover protection system is installed, producing a structurally rigid fairing body. The top-front will be produced separately and attached to the main body with hinges.

9.4 Window Manufacturing

Last year, the team built windows by building carbon-covered foam ribs over transparent plastic in the female mold. This method worked well and will be used for *Cheryl's* windows. Using thinner plastic will save weight and conform better to the mold's shape. The orientation of the panoramic windows can be seen in Figure 7.

10 Innovation

Cheryl is an all-weather vehicle which utilizes its many subsystems to allow a rider to tackle the tough elements of rain, wind, snow and ice on their ride. This versatile a vehicle has not yet been constructed in the HPV world. The combination of separated wheel and rider fairing compartments, vehicle lights, air ducts, and interchangeable vehicle skis or skates, makes this vehicle utilitarian and practical for year round use. Though the vehicle may not reach speeds as high as our past vehicles, the design is that of a more feasible road vehicle.

Part II
Analysis

11 Rollover Protection System Analysis

The performance of *Cheryl's* rollover protection system (RPS) was simulated in SolidWorks Simulation 2013 using surface elements to determine deformation under load. The properties of the composite sandwich used were determined experimentally in 2013 by a three point bend test. This test procedure simplifies the composite rollbar as a linear, homogeneous and isotropic material. Although carbon fiber reinforced polymers have none of these characteristics, experimental testing demonstrated that these are valid assumptions for the constructed section under expected loading.

Two simulations were performed with the monocoque fixed at the seat. In the first, a 600lb load was applied to the top of the RPS at 12° from vertical. Next, a 300lb side load was applied at shoulder level. The maximum simulated deflection was measured as 28mm for the top load case and 14mm for the side load case. In both cases, the greatest stresses occur at the tip of the overhang above the rider. This region will be heavily reinforced on the competition vehicle.

It is notable that these simulations assume that the seat back wall has the same section properties as the main RPS hoop. Although both will be made of carbon-laminated foam, the seat will not be covered in Kevlar, changing the modulus of the system. Overall, the finite element analysis results presented are expected to be overestimates due to likely geometrical imperfections and anisotropy of the material. However, the factor of safety of almost 2 gives the team confidence in the strength of *Cheryl*.

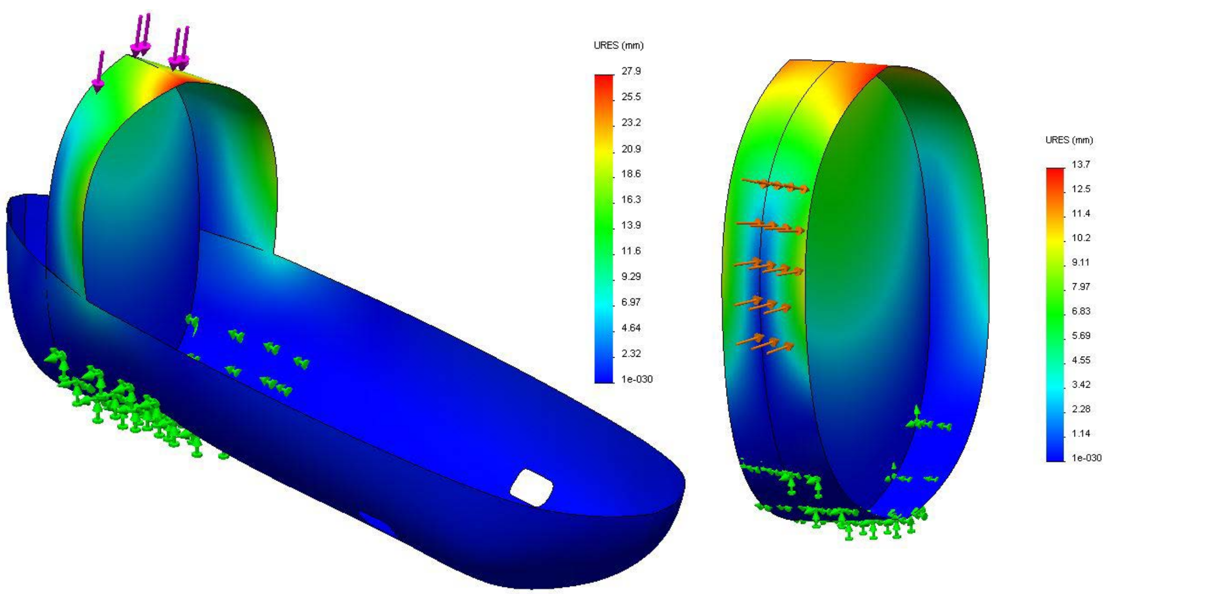


Figure 9: Simulated displacement of the rollover protection system when subjected to a 600lb top load at 12° from vertical (left) and a 300lb side load at shoulder level (right).

12 Structural Analysis

12.1 Front Frame

Cheryl's front sub-frame experiences heavy loading from rider pedaling and the front wheels of the vehicle. Finite element analysis (FEA) was performed on the frame using surfaces in SolidWorks Simulation 2013 to evaluate its load capacity.

The frame was fixed by its three connection points to the monocoque - one at the front and two at the rear. Upwards forces of 125lbs were applied to each of two wheel support points. Finally, a 200lb remote load was added at the pedal position to account for the force and moment from pedaling.

The simulation identified potential problems with the rear monocoque connection points (Figure 10). Although this area has a simulated factor of safety below one at the joint, the additional material due to the fillet weld will significantly increase the cross sectional area beyond that in the model, increasing the factor of safety to an acceptable level. Furthermore, the simulation modeled the connection points between the tubes as entirely hollow when in reality, the notched joint is not weakened by cutting out its center. This area will also be monitored closely and gussets will be added if problems are identified during testing.

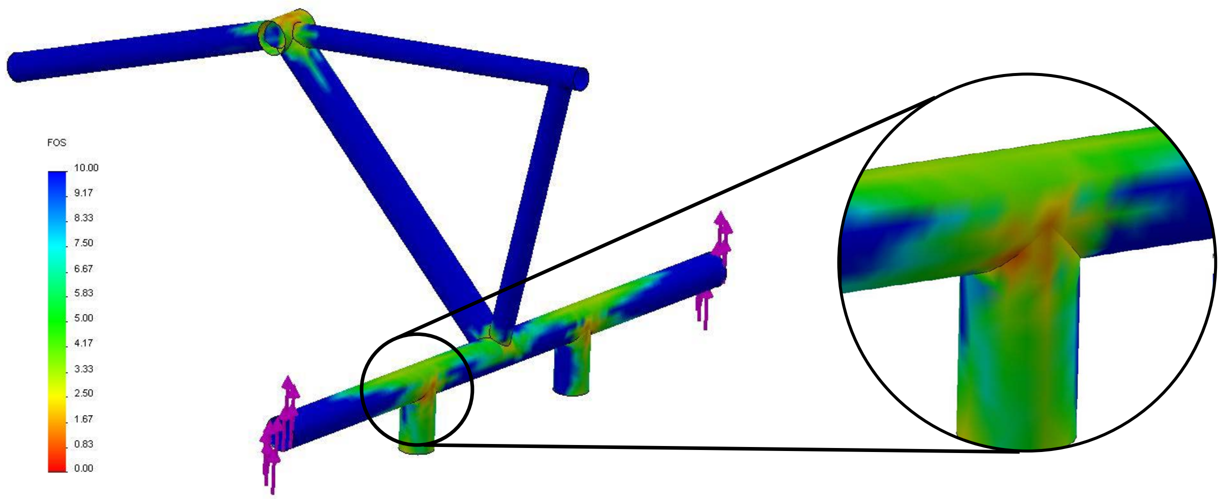


Figure 10: Front frame finite element analysis results. Note the low factor of safety at the rear monocoque connection points.

12.2 Knuckles

The knuckles that support *Cheryl's* front wheels are of special concern due to their exposure and the cantilevered nature of the wheels. Of greatest concern are the loads experienced by the knuckle should one of the front wheels leave the ground during cornering or rollover (Figure 11). The weight of the rider and the vehicle was estimated at 250lb. It is also notable that these are static loads; if the vehicle hits a disturbance on the road, the loading will spike to much higher levels. Furthermore, *Cheryl* is designed to be durable and increasing the factor of safety decreases the effects of fatigue on the parts. With these considerations, a minimum factor of safety of 3 was designed into all knuckle parts.

The knuckle, knuckle mount and wheel shaft carry the load of the vehicle and were simulated for the one-wheel loading case using SolidWorks Simulation 2013. All were subjected to a 250lb upwards force at 10° from vertical, remotely loaded at the tire contact patch. All simulations returned factors of safety greater than one (Figure 12). The first failure mode of the system is expected to be the bending of the tabs on the knuckle mount. This region will be modeled while testing *Cheryl* and will be reinforced if necessary.

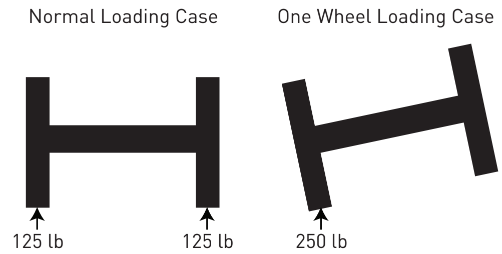


Figure 11: Knuckle loading cases.

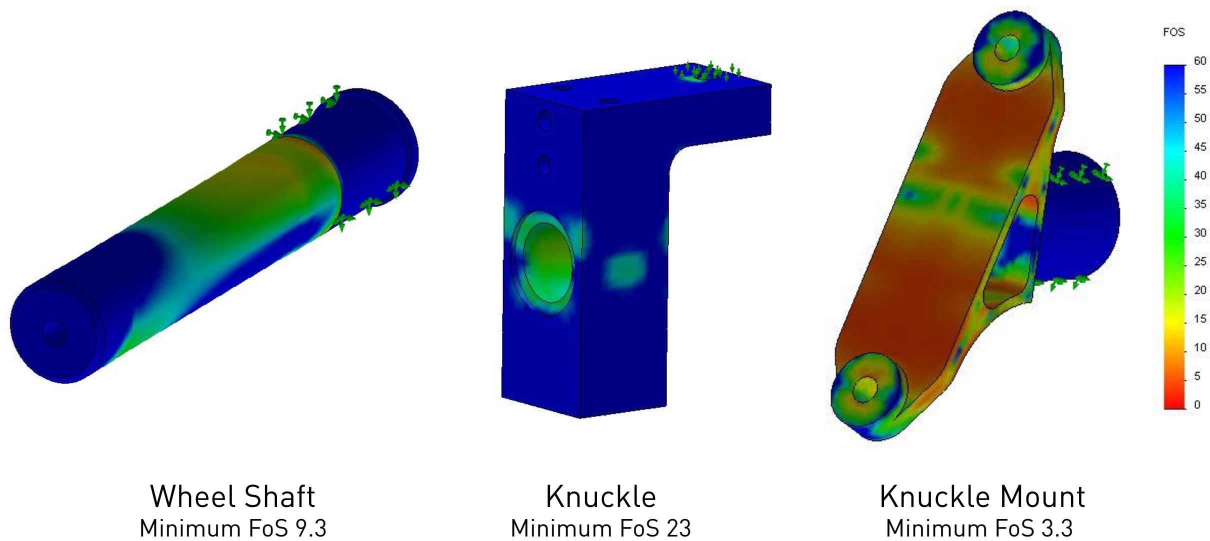


Figure 12: Knuckle loading cases.

13 Aerodynamic Analysis

Computational fluid dynamic (CFD) analysis was used to inform and guide the design of *Cheryl*. The team considered several vehicle configurations including a unified fairing containing the three wheels, a central fairing with side wheel shells and a recumbent bicycle.

13.1 Drag Force

Cheryl's aerodynamic shell was tested with CD-adapco's STAR-CCM+ CFD simulation software and compared to past recumbent bicycles and a wider three-wheel tricycle fairing. The simulations assume a vehicle speed of 30mph and include the effects of the ground moving under the vehicle. Modeling the ground prevents drag coefficient infla-

	Head-On			Crosswind
	F_D (N)	C_dA (m^2)	C_d	F_D (N)
Cheryl (2014)	8.98	0.082	0.185	307
Cheryl (Center Only)	4.12	0.037	0.104	-
The Plaid Panther (2013)	3.60	0.033	0.094	337

Figure 13: Aerodynamic Simulation Results. Note that Cheryl has significantly more drag than The Plaid Panther.

tion and gives more accurate measurements. The wheels are modeled as solid nonrotating bodies. Fairing performance depends on drag force, which is a function of drag coefficient, frontal area, air density and velocity. Factoring out the constants yields the comparison metric $C_d A$.

Preliminary simulations demonstrated little difference between the central tricycle fairing with wheel shells and full tricycle fairing - the single fairing's lower drag coefficient was offset by an increased frontal area. Given these results, manufacturability and weather-related concerns drove the decision to move forward with a central fairing with wheel shells. CFD was used to iterate upon the initial models to a more aerodynamic shell. After simulation, $C_d A$ values were derived for *Cheryl* and for last year's vehicle, *The Plaid Panther* (Figure 13).

Cheryl's center shell alone has significantly more drag than *The Plaid Panther*, a difference that can be attributed to the shorter, wider fairing and the more blunt shape leading to a large stagnation region at the tail (Figure 14). Furthermore, once the outboard wheels are added, the difference is more than a factor of two. However, *Cheryl's* fairing is still significantly more aerodynamic than an upright bicycle and thus meets the team's design goal of improving the aerodynamics of the vehicle. Although aerodynamics were not the top priority of the team this year, methods of improving *Cheryl's* aerodynamics including a redesign of the wheel covers and the addition of aerodynamic features to the wheel support bars will be explored.

13.2 Crosswind Analysis

Additional simulations were performed for both *Cheryl* and *The Plaid Panther* to determine the vehicle's performance in a crosswind. A 10mph crosswind was added to the 30mph frontal air velocity of the head-on drag simulations. *Cheryl* has about 10% less crosswind drag than *The Plaid Panther* due to its lower and less blunt side profile (Figures 13 and 15).

On a tricycle, a crosswind moment will push against the lateral friction force between the wheels and the ground. This is unlike a traditional recumbent bicycle where a sideways moment induces a lean. Given *Cheryl's* crosswind drag, the vehicle's tires must have a minimum coefficent of friction of 0.28, assuming a 250 lb vehicle with dry Coulomb friction. This value is significantly lower than expected, indicating that the vehicle will not break traction due only to a 10mph crosswind.

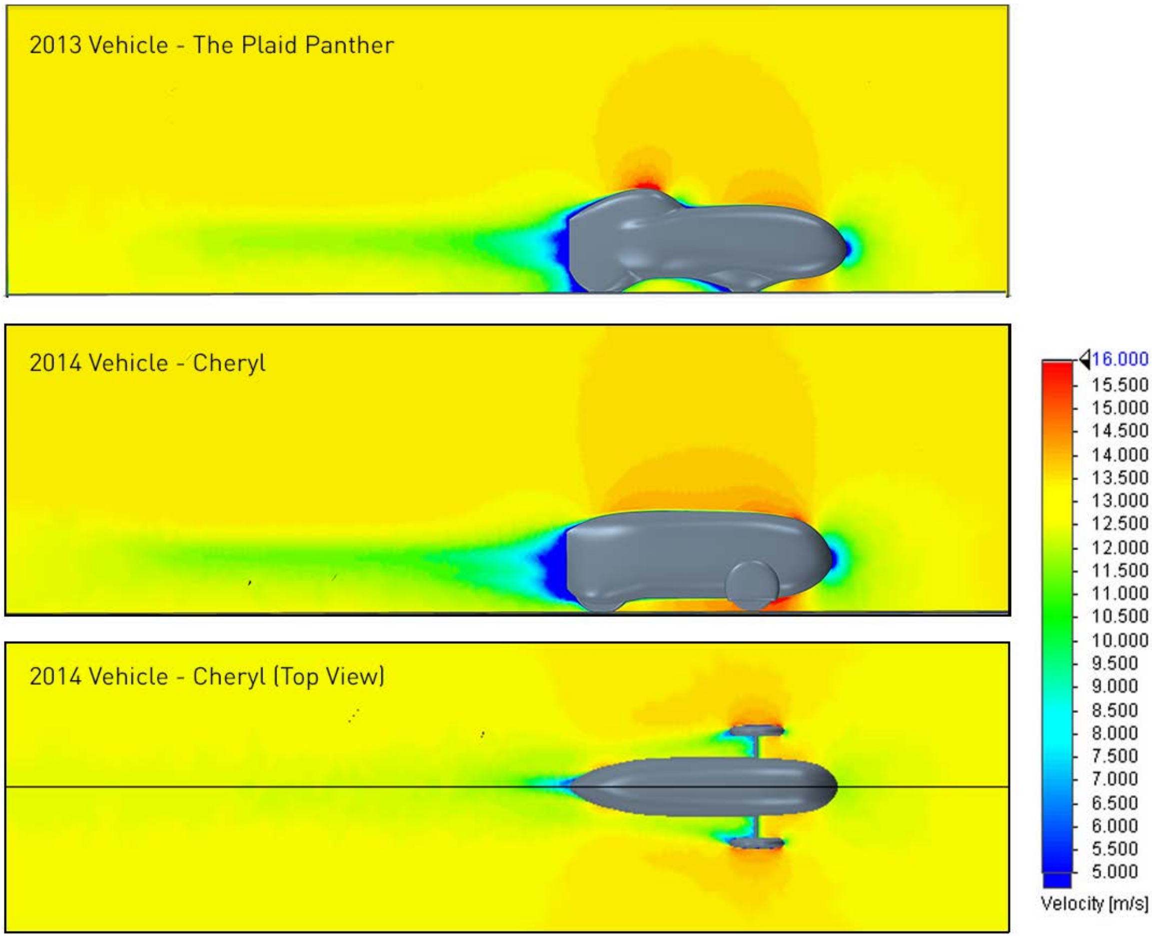


Figure 14: Simulated fluid velocity profiles for Cheryl and The Plaid Panther. Note the increased stagnation regions behind Cheryl's wheels and tail.

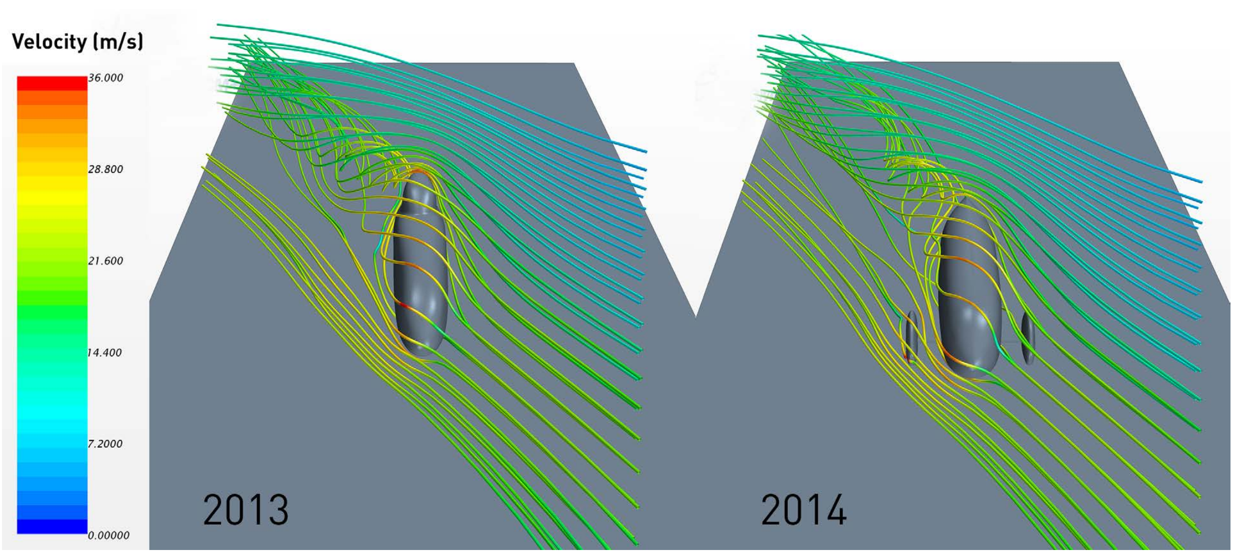


Figure 15: The crosswind flow profiles demonstrate Cheryl's improved crosswind aerodynamics. Note the decrease in major flow disturbances around Cheryl compared to The Plaid Panther.

14 Turning Radius

Cheryl's turning radius was determined experimentally using the prototype tricycle as 3' 10" measured from the outer front wheel. From the inner wheel, the turning radius is 2' 5.5". This is the maximum actuation turn with a caster angle of 6°.

This turning radius is dramatically smaller than any of our prior vehicles; *The Plaid Panther* had a roughly 15' turn radius. *Cheryl's* turning radius is on par with the radius needed to complete a 90° turn on a standard walking path, giving *Cheryl* utility in situations in which past vehicles have failed. Furthermore, the HPVC utility endurance race features a 8m radius hairpin turn and a slalom with 9m center spacing. Furthermore, satellite imagery of the drag course at the 2014 ASME HPVC East reveals no turns which approach *Cheryl's* turning radius, indicating that this agile vehicle will have no problem completing the courses at competition.

15 Visibility Analysis

Cheryl's design reclines the rider to a very low position, spawning concern over rider visibility. One of the largest concerns was that the low position places the handlebars in the line of vision of the rider, partially obstructing their view. This concept was tested with the team's old vehicle, *Shadowfax*, on which the seat was lowered to recline the rider to a position comparable with that of *Cheryl* . After testing with riders of varying heights, it was determined that the handlebars do not pose a significant problem since they are located at the bottom of the desired field of visibility.

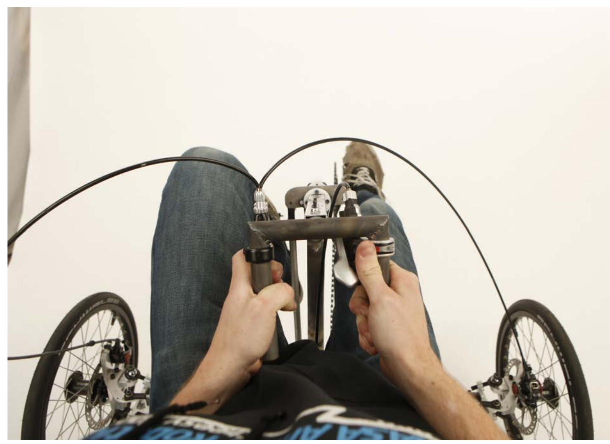


Figure 16: Super-Recumbent Rider Visibility

A view from the rider's perspective is shown in Figure 16. Unfortunately, due to the location of the RPS, visibility is obstructed, which limits the rider's peripheral vision. However, *Cheryl's* panoramic side windows give the rider almost 150° of visibility, enabling safe operation in most environments.

16 Race Simulation

16.1 Summary

The team developed a simple race simulator that models the vehicle on the race course in order to quantify the effect of changing various design parameters. This allows the team to, for example, decide whether a design change that increases vehicle mass by 10kg but decreases the C_dA by $.01m^2$ will improve or harm final race performance. This model is based on a number of physical approximations and estimates of vehicle parameters, which are based upon vehicle testing, and have been validated by race performance data.

16.2 Model

The model is a simple one dimensional dynamic simulation that takes into account the four main forces on the vehicle during operation. These forces, as well as the assumptions made in creating a mathematical model of the force, are detailed in Figure 17. Although the model is capable of simulating both sprint and endurance races, each is handled differently. The sprint distance is assumed to be 450m, and the model simply calculates the time it takes for the vehicle to reach that distance starting from rest. The endurance simulation is somewhat more complicated due to additional obstacles which require the vehicle to slow down or stop. Each obstacle was modeled as a complete vehicle, estimating that there were three of these stops per 1700m lap.

Force	Expression	Assumptions
Aerodynamic Drag	$\frac{1}{2}C_d A \rho v^2$	Assuming no wind and ignoring viscous effects. Taking C_dA = .06 m^2 (1.5x value from STAR-CCM+)
Rolling Resistance	mgC_{rr}	Assuming flat road. Taking Crr = .01, from our power testing measurements (see Vehicle Friction section).
Gear Train Friction Effective Force	$\frac{P_f}{v}$	Assuming constant power loss from drivetrain friction (see Vehicle Friction section). Pf = 20 W from vehicle testing. While gear train friction does not in reality produce a net force on the vehicle, this simplifies it as a force.
Thrust Force	$\frac{P_o}{v}$	Assuming constant power output of the rider. Taken as 500W for sprint and 120W for endurance.

Figure 17: Forces included in the race simulation.

16.3 Results

The model was used to perform a number of parametric sweeps to determine the change in race performance when various parameters are changed. Figure 18 shows the effect of vehicle mass, drag constant and rider power on sprint time and endurance distance. The secant line data displayed on the charts was particularly helpful for rough estimations of design change effects. For example, the fact that every kilogram of vehicle mass reduction lowers our sprint time by approximately 0.1s drove the decision to optimize *Cheryl's* design for lower mass, despite the added design time.

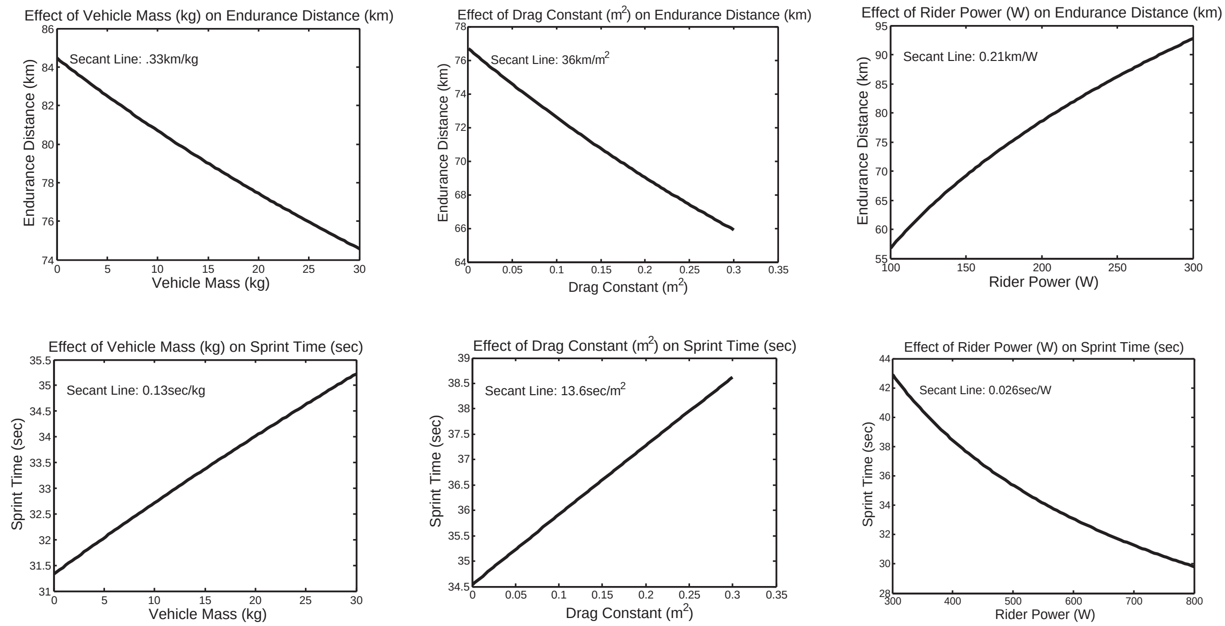


Figure 18: Summary of simulation results. Each plot shows the effect of various design parameters on endurance distance or sprint time. Secant lines give the average slope over the plot area.

17 Weight Analysis

To estimate *Cheryl's* weight, the individual weights of each sub-assembly were estimated and summed (Figure 19). The fairing is estimated to weigh 40lbs, more than half of the weight of the vehicle. Note that this includes the mounting points and attachment mechanisms for the top hatch and the front sub-frame. The front wheel assembly weighs 13lbs with most of the weight in the wheels and weldment. The back wheel assembly and drivetrain components weigh 14.5lbs. Other parts, such as the rollbar and seat, weigh 4.5lbs. The total estimated weight of the vehicle is about 72lbs.

Assembly	**Part**	**Net Weight (lbs)**	**Subtotals**
Fairing	Top half of fairing with attachment	23	
	Top half of fairing without attachment	20	
	Attachment mechanism for top half of fairing	3	
	Bottom half of fairing	17	40
Front	Front wheels	5	
	Handle bars	2	
	Front Frame Welded Structure	4	
	Steering	1	
	Pedals	1	13
Rear	Drivetrain + Chain	4	
	Rear wheel	3.5	
	External rollbar	7	14.5
Other parts	Seat	2	
	Chain pulleys	1.5	
	Wheel Mounts	1	4.5
		Total weight	72

Figure 19: Estimated Weight of Vehicle

18 Cost Analysis

Cheryl's costs are outlined in Figure 20. The estimates provided assume free labor, no major capital investment, and no bulk purchase savings.

Cost estimates for a limited-scale production run are outlined in Figure 21. Estimates are made assuming a three-year production run of ten vehicles per month, including labor costs and equipment capital investment. A bulk purchase savings of 40% on parts and raw materials is assumed.

Parts and Materials	Quantity	Price	Unit	Total
Drive train				
Chain	10	$3.75	Per Foot	$37.50
Cassette	1	$50.00	Per Set	$50.00
Derailleur	1	$50.00	Per Unit	$50.00
20" Wheel	1	$100.00	Per Unit	$100.00
Pedals	1	$35.00	Per Set	$35.00
Disc Brakes	2	$50.00	Per Unit	$100.00
Various Hardware	1	$110.00	Lump Sum	$110.00
			Subtotal	$482.50
Frame and Steering				
Steel Tube	2	$3.50	Per Foot	$7.00
Aluminum Square Tube	4	$3.70	Per Foot	$14.80
Delrin Steering Guides	2	$10.00	Lump Sum	$20.00
Tie Rod	3	$5.00	Per Unit	$15.00
Aluminum Stock	1	$30.00	Lump Sum	$30.00
16" Wheels	2	$60.00	Per Unit	$120.00
Thin Walled 4130 Steel Tubing 1.25"	4	$4.50	Per Foot	$18.00
Cromoly Tube 1.75"	4	$5.50	Per Foot	$22.00
Bottom Bracket	1	$25.00	Per Unit	$25.00
Various Hardware	1	$35.00	Lump Sum	$35.00
			Subtotal	$100.00
Fairing				
Carbon Fiber - 6K HS 50"	7	$35.00	Per Yard	$245.00
Carbon Fiber - 2K Twill 50"	3	$32.00	Per Yard	$96.00
Kevlar - Twill	2	$19.00	Per Yard	$38.00
Epoxy System	0.5	$65.00	Per Gallon	$32.50
Vacuum Bagging Supplies	1	$280.00	Lump Sum	$280.00
PETG (2' x 6' x 0.030")	1	$30.00	Per Sheet	$30.00
			Subtotal	$721.50
			Parts and Materials Total	$1,304.00
Tooling				
Fairing Mold				
Fiberglass Fabric - 50"	7	$9.00	Per Yard	$63.00
Fiberglass Basalt - 50"	7	$8.00	Per Yard	$56.00
Carbon Fiber - 8K Quad 24"	3	$10.00	Per Yard	$30.00
Epoxy System	1.5	$65.00	Per Gallon	$97.50
Vacuum Bagging Supplies	1	$100.00	Lump Sum	$100.00
			Subtotal	$346.50
Frame Jig				
Thin Walled 4130 Steel Tubing 7/8"	6	$3.50	Per Foot	$21.00
Thin Walled 4130 Steel Tubing 1.25"	3	$3.70	Per Foot	$11.10
			Subtotal	$32.10
			Tooling Total	$378.60
			Total Cost (Single Vehicle)	**$1,682.60**

Figure 20: Cost Estimate for the production of Cheryl .

Parts and Materials	Quantity	Price	Unit	Total
Bulk Purchase Discount		40%	Percent Saved	
Production Run Materials	10	$782.40	Per Vehicle	$7,824.00
			Parts and Materials Total	$7,824.00
Tooling				
Frame Jig	1	$32.10	Per Month	$32.10
Fairing Molds	1	$346.50	Per Month	$346.50
			Tooling Total	$378.60
Overhead				
Building Rent	1	$1,500.00	Per Month	$1,500.00
Utilities	1	$400.00	Per Month	$400.00
Welder Operating Costs	1	$20.00	Per Month	$20.00
Machine Maintenance	1	$20.00	Per Month	$20.00
			Overhead Total	$1,940.00
Labor				
Machinist/Welder	3	$3,200.00	Per Month	$9,600.00
Composite Technician	3	$2,080.00	Per Month	$6,240.00
Floor Worker	4	$1,600.00	Per Month	$6,400.00
Manager	1	$4,800.00	Per Month	$4,800.00
			Labor Total	$27,040.00
			Monthly Total	**$37,182.60**
Capital Investment				
CNC Router	1	$15,000.00	Initial Purchase	$15,000.00
CNC Mill	1	$22,000.00	Initial Purchase	$22,000.00
Lathe	1	$20,000.00	Initial Purchase	$20,000.00
Water Jet Machine	1	$30,000.00	Initial Purchase	$30,000.00
Welder	1	$3,500.00	Initial Purchase	$3,500.00
Grinder	1	$150.00	Initial Purchase	$150.00
Band Saw	1	$2,000.00	Initial Purchase	$2,000.00
Vacuum Pump	1	$350.00	Initial Purchase	$350.00
			Capital Investment Total	**$93,000.00**

Production Cost Prediction by Month

Months	Total Cost	Cost Per Vehicle
1	$130,182.60	$13,018.26
3	$204,547.80	$6,818.26
6	$316,095.60	$5,268.26
12	$539,191.20	$4,493.26
24	$985,382.40	$4,105.76
36	$1,431,573.60	$3,976.59

Figure 21: Cost estimate for a limited production run of Cheryl -like vehicles.

Part III
Testing

19 Rollover Protection System Testing

As *Cheryl's* fairing is not yet complete, testing was conducted on *The Plaid Panther's* rollover protection system (RPS) in order to verify and refine this year's design. The RPS in the new vehicle has been designed to be significantly stronger than the system in *The Plaid Panther*, replacing steel reinforcing tubes with a full carbon back wall for added stiffness. Once complete, *Cheryl's* rollover protection system will be tested per ASME HPVC regulations.

A direct compressive load was applied at 12° from vertical to the top of *The Plaid Panther's* RPS on an Instron 5582 Universal Tester. The force was distributed over the top of the vehicle by a slice of foam which did not significantly deform during the test. The monocoque was supported immediately below the rider's seat and the force-deformation curve was measured.

Figure 22 shows the results of the test. The test suggests that the fairing can withstand the required 600lbf load, though only just before the maximum 2" of deflection. This narrow success can be attributed to accumulated damage from crashes and rollovers, and flawed manufacturing techniques. One memorable incident in particular involved an Olin rider who was blown by a hearty gust off a parking lot and rolled repeatedly and violently down the face of a grassy knoll.

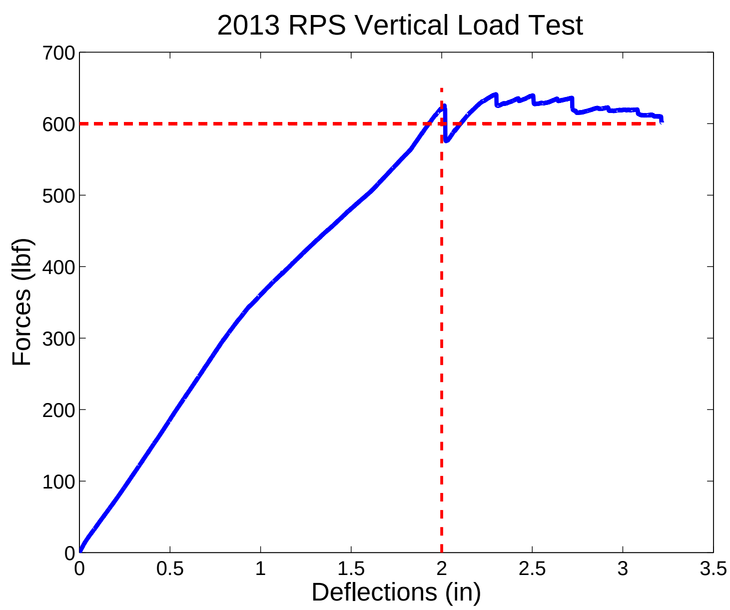


Figure 22: Vehicle fairing load test.

A visual inspection of the fairing during loading yielded a number of qualitative observations that will influence our fabrication and design this year. Some signs of delamination were visible between the two layers of carbon fiber separating the outer shell and the rollbar. This separation was likely triggered during the grassy hill incident from last year and was only exacerbated during our testing. The team is seeking to eliminate delamination through better preparation of bonding surfaces between layers of carbon and the use of vacuum bagging on the rollbar. Preparation of the bonding surfaces primarily involves thorough sanding and cleansing before the second carbon layup.

Last year, our carbon rollbar was supported by two steel tubes that attached to the inner sides of the fairing, which successfully constrained the fairing at its mounting points. However, the tube did not manage to keep the rest of the carbon sides from bowing outwards dramatically during testing. This problem will be ameliorated by replacing the pair of steel support tubes with a wall of carbon fiber. This wall will provide continuous radial support for the fairing and more effectively prevent bowing.

20 Developmental Testing

20.1 Leaning Tricycle Prototype

In the fall, the team built a prototype delta-style leaning tricycle. The focus of this development cycle was to create a novel leaning steering mechanism and an adjustable drivetrain. The leaning mechanism allows for rear-wheel, lean-only steering and self-centers after the turn. The drivetrain features an adjustable pinboard to accommodate varying rider heights. However, the vehicle proved difficult to control and had an unreasonably large turning radius. This prototype allowed the team to explore a new design direction and investigate the feasibility, issues, and potential of tricycle designs. This testing drove the decision to design this year's competition vehicle as a tadpole-style tricycle.

Figure 23: Tadpole Tricycle Prototype

20.2 Tadpole Tricycle Prototype

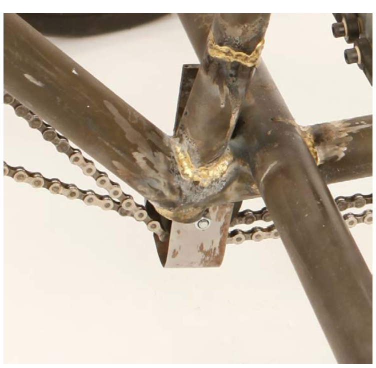


Figure 24: Fully-contained chain idlers keep the chain on the pulleys.

After preliminary design for the competition vehicle was complete, the team constructed a prototype vehicle in order to test the handling and performance of the chosen steering geometry (Figure 23). The prototype is based on the competition vehicle CAD model, with the carbon monocoque replaced by a steel frame. This prototype was designed to be adjustable and highlighted several notable strengths and failures of the design.

The most significant issue exposed in testing was the difficulty of steering. While riders were able to apply the necessary torque to the steering bars, it was difficult and uncomfortable. The team designed and tested two solutions to this problem. First, the steering torque was reduced by halving the front wheel caster angle from 12° to 6°, though at the expense of poorer centering. Second, the mechanical advantage of the steering wheel was adjusted, maintaining caster but reducing the minimum turn radius of the vehicle. After testing, the team determined that a reduced caster angle will best meet the design requirements and allow a rider to maintain a tight turning radius.

In addition to steering difficulty, the prototype initially had issues with the chain falling off of the chain idlers. When a load is applied to the pedals, the drive chain tensions and the return chain is left with so much slack that it falls off the chain idler pulleys. This was solved by fully enclosing the chain in the idlers so that it cannot fall off (Figure 24).

Finally, the prototype tricycle highlighted the importance of laterally constraining the rider in the vehicle. Non-leaning tricycles apply large lateral forces on the rider during cornering. On the prototype, the rider tends to slide out of the seat when taking sharp turns. The side walls of the monocoque on the competition vehicle will constrain the rider and allow for maximum control and power output.

20.3 Fabric Fairing

Figure 25: Four point bend testing was performed on all candidate fabrics.

All of the team's prior vehicles have had composite fairings. This year, the team investigated implementing a fabric fairing on the vehicle. A fabric fairing could dramatically reduce the weight of the vehicle, improving performance and utility.

The team decided that any fabric employed in the fairing must be durable, conform easily to a support structure, and still be stiff enough to resist deforming due to wind resistance at high speeds. Originally, air permeability was considered as a factor in fabric selection, but research on fabric aerodynamics by Oggiano et al[3]. suggests that drag due to deformation of the fabric far exceeds any drag generated by the semi-permeability of the fabric. Consequently, the team disregarded permeability when examining textile candidates.

Seven fabrics were evaluated that are used in tents (Laminated Ripstop and 30 Denier Nylon Ripstop), rain jackets (Gore-Tex Waterproof Nylon and Gore-Tex Breathable Nylon), flexible applications (Paramount Nylon/Spandex and Polyurethane [PU] Coated Nylon/Spandex) as well as polyester / dracon heat shrink material. As there are no relevant American Society for Testing and Materials (ASTM) fabric stiffness standards, four point bend testing was used to determine the load necessary to deform the fabric by 1cm (Figure 26). All seven fabrics were tested in orthogonal directions and forces were measured with an Instron Universal Testing Machine (Figure 25).

Fabric	Fabric Direction	Load (N)
Paramount Nylon/Spandex	Weak	0.40
	Strong	0.46
PU Coated Nylon/Spandex	Isotropic	0.45
Gore-Tex Waterproof Nylon	Weak	2.65
	Strong	11.81
30 Denier Nylon Ripstop	Isotropic	7.05
Heat Shrink	Isotropic	24.28
Laminated Ripstop	Isotropic	27.27
Gore-Tex Breathable Nylon	Isotropic	28.54

Figure 26: Fabric bend test results show load required for 1cm of deformation. Note that only anisotropic fabrics were tested in multiple directions.

In addition to bend testing, wind tunnel testing was attempted with fabric wrapped around a ribbed test specimen (Figure 27). Unfortunately, the team was unable to sew the fabrics onto such a small specimen and the size of our wind tunnel prohibited larger samples.

Figure 27: Ribbed test specimen for wind tunnel testing.

These findings suggest that the Gore-Tex Breathable Nylon and the 30 Denier Nylon Ripstop are most suitable for use in human powered vehicle fairings. Though the Heat Shrink and Laminated Ripstop fabrics were stiffer than the 30 Denier Nylon, they were too difficult to work with. The Gore-Tex Breathable Nylon and the 30 Denier Nylon Ripstop meet the specifications of durability, workability and stiffness. Although carbon fiber monocoque fairing construction had begun by the time fabric tests were completed, the team will use these results should the team consider a fabric fairing in the future.

20.4 Male Mold

After experiencing the cross pollination of many ideas between teams at competition last year, the team decided to test a mold construction method inspired by the University of Toronto's 2013 manufacturing process. The team considered applying a sacrificial foam mold approach to the 2014 vehicle. In order to gain experience with this approach, a large male-molded monowheel was prototyped in the Fall 2013 semester. This consisted of a 7' foam disc that was covered in carbon fiber. Results from this experiment showed that good surface finish requires much post-lay-up work, composite placement is more important than with female mold (for surface finish), and that we can vacuum bag directly to a composite surface. The team decided not to proceed with this method of manufacturing due to lack of experience and because the perceived benefits did not outweigh the potential risk of inadequate surface finish after such a large investment of time.

Figure 28: Male and Female Test Molds

20.5 Mold Style

The team has historically used a CNC router to construct a foam male mold, which has then been sanded smooth. Fiberglass molds are then constructed using the male plug. This process is time consuming, but yields excellent surface finishes if done correctly. In an attempt to reduce labor, the team experimented with routing a female mold out of foam. To test this process, a pair of foam test pieces was routed, one male plug and one female mold, pictured in Figure 28. The team then worked toward making a mold with both processes, taking note of the difficulties and benefits of each approach.

The female mold proved to be difficult to sand, especially for smoothing the transitions between the 2" foam sheets which made up the mold. It also resulted in a far worse surface finish than the male plug with fiberglass female mold. The routed edges made alignment incredibly simple, a feature which both methods shared. From this research, a multi-part male plug to female mold was deemed the best path for *Cheryl's* fairing as it maximized efficiency for the level of finish desired.

20.6 Carbon Tube Attachment

The team has always been intrigued by the possibility of using carbon fiber structural tubes on team vehicles. Carbon tubes have an extremely high strength to weight ratio and could lighten the vehicles substantially. This year, the team tested the performance of carbon tubes and some attachment methods. Specifically of interest their uses in *Cheryl's* steering column or steering tie rods.

First, a compression test was done on a 1" OD x 0.066" wall x 2" long carbon fiber tube on an Instron 5582 Universal Tester. After 13.9ksi of axial stress, a crack formed along the weave at approximately 45° from axial, winding down the tube. This is a larger load than expected for either of the potential use cases on *Cheryl* .

Next, 2" long aluminum plugs were epoxied into the ends of a 1" OD x 0.066" wall carbon tube. If used in *Cheryl's* steering, these plugs would attach to ball ends to control the front wheels of the vehicle. Mating surfaces were sanded before bonding to improve the strength of the adhesive connection. The plugs were attached to the Instron Tester and the connection was tested in tension. The adhesive connection failed at 4051lbf for a shear strength of 737psi, weaker than expected.

Overall, although carbon tubes are a promising technology, our tested methods of tube attachment are too heavy to give carbon tubes an advantage in *Cheryl's* steering. The team plan to continue researching and testing methods of carbon tube attachment in the future.

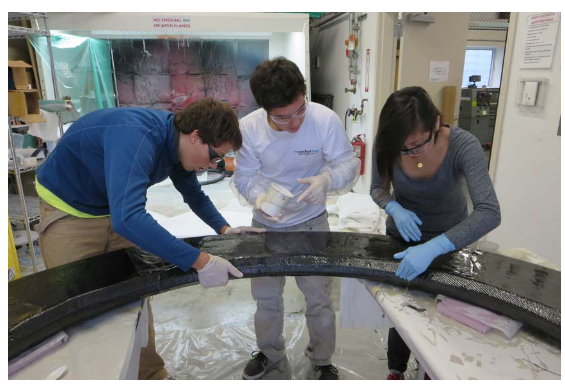


Figure 29: New and veteran team members work together on monowheel production.

20.7 Team Structure

This year, the team decided to alter its internal organization to provide more opportunities for all members to gain knowledge and experience. During the fall semester, the team held a vehicle design challenge, in which the team split in half to quickly produce two prototypes: a leaning tricycle and a monowheel. The purpose of the design challenge was to get new members acquainted with design, manufacturing, and teamwork. Although the two resultant vehicles were not intended to compete, some system designs and manufacturing techniques were adopted for the competition vehicle. Because of the vehicle design challenge, the team retained many members for the spring semester, holding the record for the most members in team history.

The primary goal of the spring semester was to construct the competition vehicle. In order to promote efficiency and enthusiasm for working on the vehicle, the team decided to adopt a fast-paced two week task cycle. By assigning short term tasks that were required to be completed at the end of the two week period, team members were able to work with new people and learn a more diverse set of skills. Additionally, this structure empowered new members to take ownership of tasks, while being supported by experienced members.

21 Performance Testing

21.1 Dynamometer Testing

21.1.1 Apparatus

To test the power output of our riders, the team built a dynamometer by modifying a treadmill. To accommodate testing of a range of wheel sizes, the distance between the two rollers on the treadmill was shortened by modifying the treadmill's support beams. A circuit was then built from two components, a voltage divider and a filter, to extract data from the dynamometer using a standard oscilloscope and voltmeter. The apparatus is shown in Figure 30.

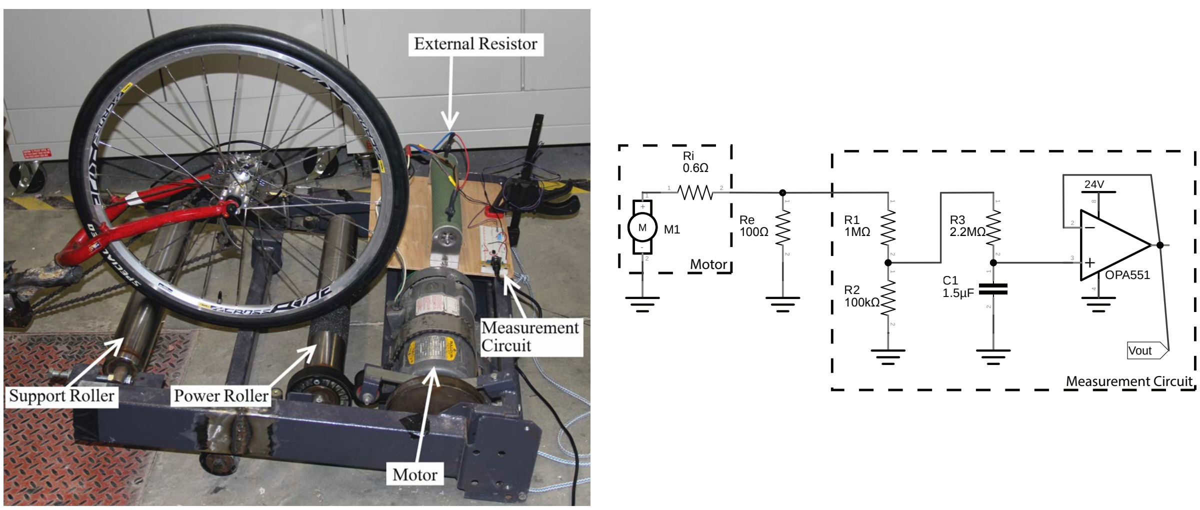


Figure 30: The dynamometer apparatus. Left: The dynamometer electrical system. Right: a picture of the dynamometer with the tricycle.

21.1.2 Power Testing

The dynamometer was used to test the power output of various riders on a standard bicycle. By assuming no current through the measurement circuit, the electrical power dissipated by the resistor is calculated as $P = \frac{V^2(R_e+R_i)}{R_e^2}$. However, a significant amount of power goes into overcoming the mechanical friction of the bike and apparatus. The frictional power losses were determined by using the friction measurements with the rider sitting on the bike, and approximating a linear dependence between speed and frictional torque (see *Friction Measurement* below).

The power output of several team members is shown below in Figure 31. There is a wide variation between team members. This information will help the team choose riders (currently Alex and Sarah seem likely candidates for the sprint race) for the competitive races, as well as help riders track themselves in their pre-competition training.

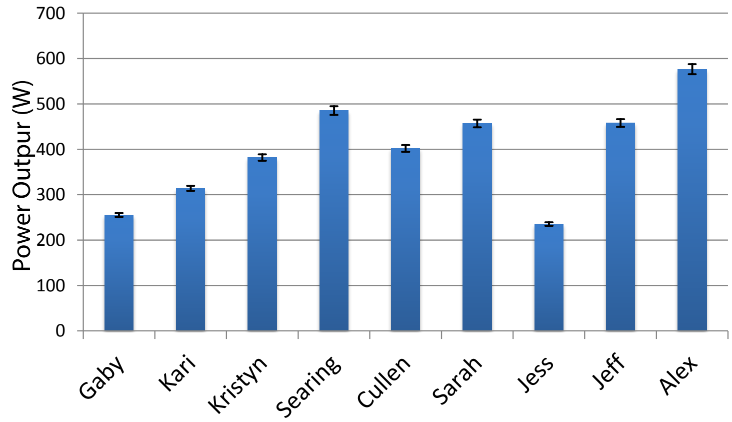


Figure 31: Average power output over 15 seconds for 9 team members. The error bars were determined by assuming perfectly precise electrical power measurements, and propagating the standard errors of the mechanical power regression into the power equation.

21.1.3 Friction Measurement

In addition to power testing, the friction of vehicles can be measured by using the dynamometer in reverse: powering the motor with a large power supply and measuring the I-V curve. In DC motors, the torque applied is directly proportional to the current, and the speed of the motor is directly proportional to the voltage drop. Using these facts and mechanical advantage conversions, the frictional torque of the drivetrain was determined as a function of speed.

The vehicle friction measurements are shown in Figure 32. The recumbent bicycle (a prototype vehicle from 2012), recumbent tricycle (this year's prototype) and upright bicycle (an older mountain bike) show little difference in their friction functions. When the rider sits on the tricycle, the friction increases dramatically. At speeds greater than 1m/s, the slope of the friction-velocity curve is approximately the same with and without the rider, but with a displacement of roughly 7N that is likely due to rolling resistance, which should increase proportionally with weight. This value can be used to estimate the coefficient of rolling resistance. This value of 0.1 is used for the race simulator.

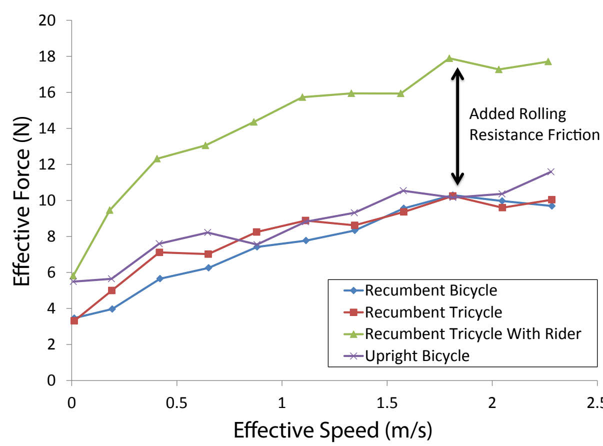


Figure 32: Friction measurements for various vehicles

A linear regression over points with effective speed greater than 0.5 m/s was used to approximate the friction function for the *Power Measurement* section above. The regression for the tricycle with rider, which was used to calculated mechanical power, gave $F = (0.0129 \pm 6.5E - 4\frac{Ns}{m}) * v + (2.342 \pm 0.0199N)$.

It is important to note that, because of gearing, the friction curves of Figure 32 should not be extrapolated to higher speeds. In normal operation, the rider will shift gears so as to keep the drivetrain moving at an approximately constant speed, independent of ground speed. Since drivetrain friction is a function of velocity, it will remain approximately constant during normal operation. To measure this friction, we shifted gears and measured the frictional power losses while the pedals rotated at an 80rpm cadence (the average cadence expected during the race). It was found that the drivetrain has a frictional power loss of 21W. This value was used in the race simulator.

These measurements have been partially validated by the race simulation (see the *Race Simulation* section), because these values of drivetrain friction and C_{rr} produce reasonable race performances. Thus the friction testing and race simulation analyses are consistent.

In the future, and with further developments, these friction measurements may be used to experimentally compare different drivetrain geometries.

21.2 Steel Tube Connection Strength Testing

In the past, the team has TIG welded all of our frames. This year, bronze brazing was explored as an alternative to TIG welding. While not as strong as welding, brazing is quicker and easier to perform. MIG welding was not considered due to the difficulty of welding thin materials with the equipment available. Testing was performed to determine the relative strengths of brazed and welded joints.

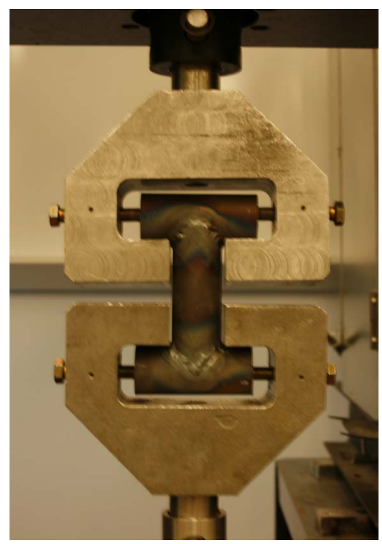


Figure 33: Steel tube connection test setup.

Six I-shaped samples were prepared of 1.25" diameter, 0.035" wall thickness 4130 chromoly steel tube (Figure 33). Half were TIG welded and half were capillary and fillet brazed with bronze filler rod. The TIG welded tubes withstood a mean load of 20.5kN before yield, nearly twice the 11.3kN supported by the brazed tubes. Stresses were not calculated due to the difficulty of finding the cross-sectional area of the connection.

Although the TIG welds were much stronger, bronze brazing is easier to work with, especially with large gaps and difficult geometry. After testing, TIG welding was employed as the primary connection method on *Cheryl*.

21.3 Weather Testing

Cheryl was designed to be a practical vehicle for use in all weather conditions including New England winters. To evaluate the vehicle's handling in adverse weather, the prototype vehicle was tested on a variety of different road surfaces. On snow (Figure 34b), the prototype was agile, maneuverable and did not skid. Furthermore, during testing on a nearby hockey rink with slick road tires, the vehicle was completely stable, even during tight turns and slides (Figure 34a). Additionally, in casual and aggressive street riding, the vehicle handles intermittent patches of ice and crusty snow with ease. Finally, testing with past faired vehicles has demonstrated the impressive wind-shielding advantages of fairings. Increased stability and protection from the elements has a dramatically positive effect on rider confidence and places *Cheryl* in a class of its own.

Figure 34: Prototype Tricycle Ice (left) and Snow Testing (right)

Part IV
Safety

22 Design for Safety

Safety is a top priority on the Olin Human Powered Vehicles Team. The vehicle is designed not only to be aerodynamic and efficient, but also to protect the rider within. *Cheryl's* design includes not only a rollover protection system and seatbelt but also additional features that prevent harm to the riders in the event of an accident or misuse of the vehicle. A tricycle design provides more balance and stability than last year's two-wheeled vehicle, reducing the chance of capsize and providing easier ingress and egress. In the off chance that the vehicle rolls over, the vehicle's monocoque fairing and rollover protection system will protect the rider from contacting the asphalt or other elements that may cause injury. As always, the rider will be wearing a helmet when operating *Cheryl* .

Despite the tight fit between rider and fairing, the inner components of *Cheryl* pose little danger to the rider. All parts near the rider are rounded or padded as appropriate to prevent scratches or cuts from sharp edges. Because this year's design requires the rider to be seated closer and lower to the back wheel, a carbon fiber partition will separate the rider from rotating wheel. The rollover protection system is lined with Kevlar to prevent dangerous splintering in case of catastrophic failure.

23 Safety in Manufacturing

Besides rider safety at competition, safety of team members during vehicle manufacture is of paramount importance. The team works to be cognizant of all hazards throughout the manufacturing process, taking action to reduce or eliminate dangerous situations. When working near metalworking equipment or machine tools, team members are careful to tie back hair and loose clothing and wear long pants, closed toed shoes and safety glasses. In composites manufacture, safety glasses and respiratory protection are used as appropriate to protect from dust, fibers and fumes. Finally, no team member ever works on the vehicle without another person present, encouraging members to make safer decisions together. Furthermore, if the first team member were injured or in danger, the second could take action and summon help as appropriate.

24 Hazard Analyses

Hazards accompany any mechanical system. For both the safety of the rider and the overall performance of *Cheryl*, a list of possible hazards is examined and identified and solutions or temporary fixes that keep the system running and the rider safe are presented (Figure 35).

Hazard	Likelihood	Solution
Window fogs up or riders overheat	High	NACA duct in fairing directs air flow at rider and window.
Rider needs to stop suddenly		Disk brakes can quickly stop vehicle.
Flat tire or broken chain	Medium	Apply brakes and replace parts at pit stop.
Vehicle crash or rollover		Sturdy RPS, carbon fiber fairing, and extra ribbing in weak spots protect rider. Fairing can be opened from inside or
Undesired road conditions or high traffic area		Window has large field of view and riders are experienced.
Loose or damaged part on vehicle		Run vehicle to pit stop and necessary reparis will be made with available tools.
Unattended vehicle rolls away		Wheel blocks and brake lock on handlebars.
Wet conditions on track		Riders are well-trained in Boston weather and vehicle is very stiff, giving good road feel.
Glare interferes with rider		Wear sunglasses. Windows are removable.
Tie rod breaks	Low	Rollover protection system protects rider in case of loss of control. Dual disk brakes can quickly stop vehicle.
Rider cannot fit in vehicle comfortably		Vehicle is designed for a wide range of rider sizes.
Steering stuck		Disk brake quickly stops vehicle for maintenance.

Figure 35: Cheryl Hazard Analysis

Part V
Aesthetics

Cheryl was designed with the intent of creating a stable and comfortable vehicle that balances accessibility and performance. As tricycles inherently have a larger frontal area than bicycles, the team worked hard to maintain a fast and clean exterior without the intimidating aura of *The Plaid Panther*.

The fairing of the vehicle notably does not contain the two front wheels. This design choice allows for a slimmer central fairing, avoiding the clunky and round look of many commercially produced fully faired recumbent tricycles. The front wheels will instead be separately faired, bringing the fairing closer to the rider to decrease weight and improve visibility.

The fairing was also designed to fit snugly around the rider while maintaining plenty of space inside for comfort. This snug fit paired with the extremely recumbent rider position places the vehicle around the rider efficiently by removing awkward window bubbles and other shapes often integrated into previous team vehicles.

Special care was put into improving the surface quality of *Cheryl's* aerodynamic fairing over past team vehicles through extensive mold production and setup procedures. The vehicle's three-wheeled design reduces the likelihood of vehicle capsize, protecting the exterior from scrapes and surface damage. Additionally, the trike does not require landing gear. Without awkwardly protruding training wheels, the bottom of the fairing is smoother and more uniform.

As always, the team's sponsors are recognized on the side of the vehicle with decals cut out of high-adherence white vinyl for a professional and highly legible appearance. Although the exterior of the vehicle is the public-facing side of the project, effort was also put into the interior, particularly in making the interior clean, comfortable, and free of clutter. For this reason, the only subsystems integrated into the rider's compartment of the fairing are the steering and drivetrain, eschewing all three wheels from the immediate space around the rider.

Part VI
Conclusion

25 Comparison

Vehicle Design Specifications	Analytical Performance Predictions	Experimental Results
A reliable vehicle with little room for failure, giving the rider more confidence.	By increasing the factor of safety and simplicity of all mechanisms on the vehicle, the team can eliminate last minute or mid-race failures in both the endurance and speed events.	Due to the increased factor of safety for each system in the design phase, the vehicle prototype has already proven more reliable than past vehicles. There have been no failures or signs of potential failure.
A stable vehicle that is functional in a variety of situations. A More controllable and accessible vehicle.	The vehicle will be more stable than previous competition vehicles due to its constant three points of contact with the ground.	All members of the team have ridden and are capable of riding the tricycle prototype. The vehicle is already more accessible than those of past years.
A vehicle usable in different weather conditions.	Three points of contact will make it easier to ride on different surfaces. The wheel locations will prevent water from splashing into the vehicle when riding on wet surfaces. On ice, detachable wheels will will be convertable to skates or skis.	When testing the vehicle on ice the rider was able to stay in control and upright with minimal sliding.
A safe vehicle that will protect both riders and bystanders.	Increased stability will reduce the likelihood of tipping and roll-over, protecting both the rider and bystanders.	The vehicle prototype has yet to tip or cause the rider to lose control.

26 Evaluation

While it is difficult to evaluate an unfinished vehicle, the team can take insight into *Cheryl's* prospective performance from the design prototype.

The team's first goal was to build a reliable vehicle that would not experience failures during use. *Cheryl* is designed to decrease the likelihood of failure by simplifying mechanism designs. The vehicle prototype has so far proven to be reliable, inspiring confidence in the final design and implementation.

The second goal was to build a stable vehicle making it accessible to more riders. The three points of contact contribute to rider confidence. Unlike past vehicles, all team members have been able to ride the trike on their first try without assistance. This stability provides for a more useful and accessible vehicle.

The third design goal is to make the vehicle practical in different weather conditions. Easily removed wheels increase the practicality of the vehicle, because the wheels can be replaced with other mechanisms such as skis or skates in order to travel in different types of terrains. Theoretically this makes the vehicle usable throughout the year. Additional considerations, such as detached wheel pods, have been taken into account to keep the rider dry and more comfortable in poor weather commutes.

The fourth and final design goal was to make a safe vehicle. In the past the team has had issues with vehicle tipping or rolling. *Cheryl* is designed to reduce this risk and make the vehicle safer for riders and bystanders. A rider that is more in control will remain safer and prevent collisions with bystanders.

27 Recommendations

This year the team decided to focus its time in a different manner. By spending the first semester building two conceptual vehicles, team member experience designing and manufacturing vehicle systems was maximizing. Focusing time and structuring the second semester into two week design tasks allowed us to accomplish a greater variety of tasks in a smaller time period. The team would recommend future teams put significant time into schedule and task structure in order to use time efficiently and effectively. Although the concept vehicles were a valuable exercise for much of the team, they did use large amounts of team time. The team would recommend a similar, but better scoped exercise in the future.

28 Conclusion

The Franklin W Olin College of Engineering Human Powered Vehicles Team is excited this year to bring a stable, reliable, safe, and all-weather vehicle to competition. The team looks forward to racing *Cheryl* around the course from inside rather than outside. The simplicity of the vehicle takes a step back from intricate and advanced design challenges to focus on the most vital aspects of vehicle performance. This change of focus should benefit the team's performance greatly when race time comes and allow it to better achieve its goal of advancing the state of human powered technology.

References

[1] Rickey M. Horwitz, The Recumbent Trike Design Primer. *Hell-Bent Cycle Works*, 2010.

[2] Friction Facts, *Friction Facts Efficiency Report Package*, 2014.

[3] Luca Oggiano, Saetran Lars Roar, Bardal Lars Morten, and Hoying Brian, Äir permeability and drag crisis on high tech fabrics for cross country ski competitions.,Ïrocedia Engineering, 34 (2012): 15-19.