ASME SETTING THE STANDARD http://go.asme.org/HPVC	**Vehicle Description Form** (Form 6) Updated 12/3/13 **Human Powered Vehicle Challenge** **Competition Location: San Jose, California** **Competition Date: April 22-24, 2016**

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: Gold Trans Am
Vehicle number: 5

Vehicle configuration

Upright | Semi-recumbent X
Prone | Other (specify)

Frame material: Carbon Fiber-Aluminum Monocoque

Fairing material(s): Carbon Fiber, Nomex Honeycomb, Kevlar

Number of wheels: 3

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

Length 95.0 in | Width 30.3 in
Height 46.0 in | Wheelbase 45.1 in

Weight Distribution: Front 60%* | Rear 40% | Total Weight TBD**
Wheel Size: Front 16 in | Rear 20 in
Frontal area: 968 in^2
Steering: Front X | Rear
Braking: Front X | Rear | Both
Estimated Cd: 0.087

Vehicle history (e.g., has it competed before? where? when?) *Gold Trans Am was designed and built exclusively for the 2016 ASME HPV Challenge and has not yet competed before.*

**Vehicle has not been completed - weight distribution estimated.*
*** Expected weight is 84 lpf.*

Olin College OF ENGINEERING Human Powered Vehicles

2015-2016 Design Report

Gold Trans Am

Vehicle #5

Dennis Chen
Josh Sapers
Lucy Wilcox

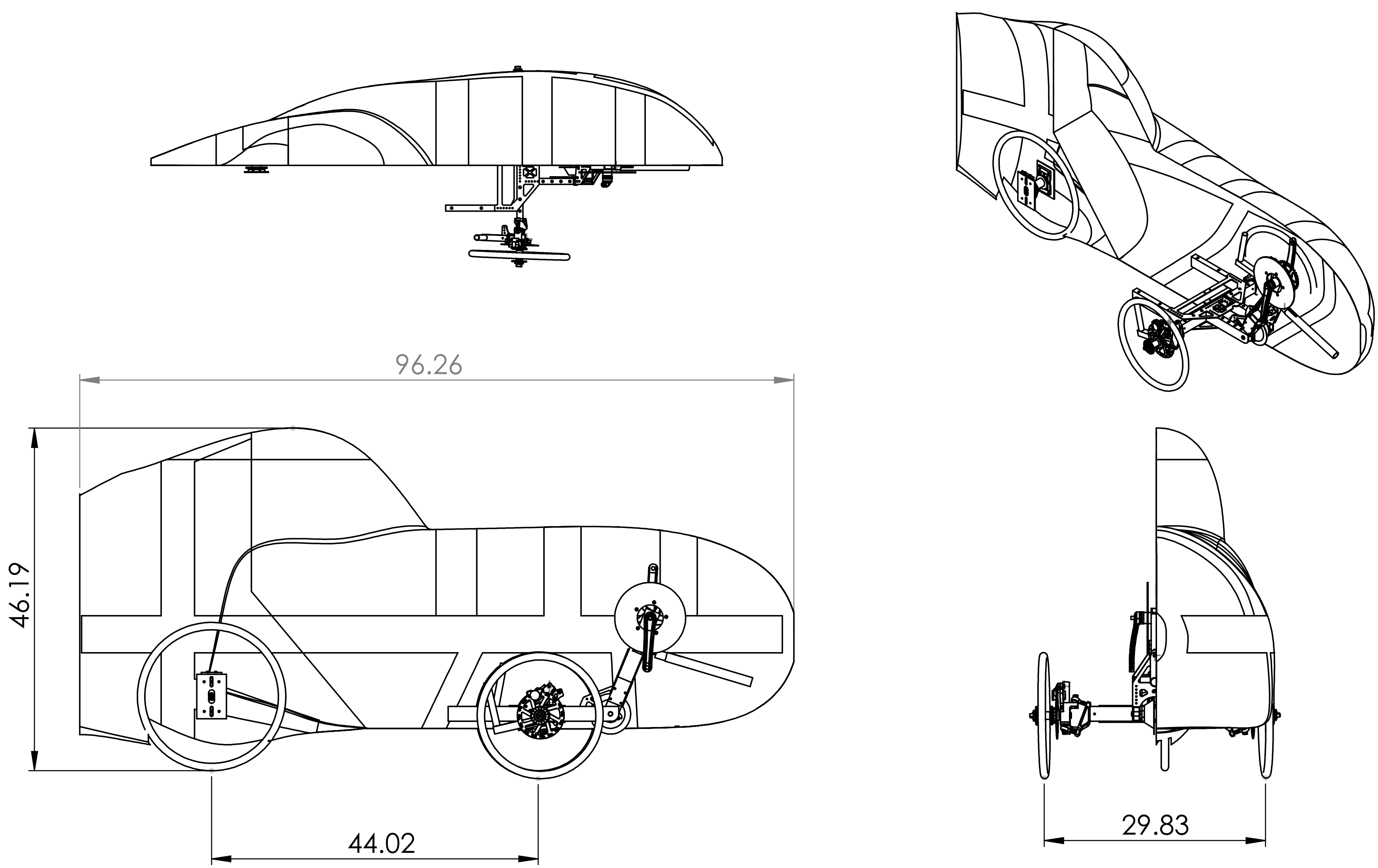
Maggie Jakus
March Saper
Nagy Hakim

Paige Pfenninger
Paul Titchener
Zarin Bhuiyan

Jennifer Wei
jennifer.wei@students.olin.edu

Kevin Crispie
kevin.crispie@students.olin.edu

Faculty Advisors
Aaron Hoover & Chris Lee
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	

SEE SOLID MODEL Gold Trans Am FOR ALL UNSPECIFIED GEOMETRY

MATERIAL: ASSEMBLY

	INIT.	DATE
ENGINEER	PT	3/22/2016
DRAWN	PT	3/22/2016
CHECKED	KC	3/22/2016

Olin College of Engineering

GOLD TRANS AM

SIZE: **B** | PROJECT: OLIN HPV 2016 VEHICLE | REV: **A**

SCALE 1:25 | DO NOT SCALE PRINT | SHEET 1 OF 1

5 4 3 2 1

Abstract

The Olin College Human Powered Vehicle Team returns to the ASME Human Powered Vehicle Challenge with *Gold Trans Am*, its 2016 vehicle. This year's vehicle is very similar to last year's vehicle, *Llama Del Rey*, in both form and performance. The team's performance at the 2015 competition led the team to focus on the following areas:

1. *Gold Trans Am* will have an improved chain routing system. Last year, the team struggled with the chain routing system and did not make the design a priority until the end of the design process, resulting in a chain malfunction at competition. This year, both fairing design and frame design focused heavily on chain routing. This is advantageous because it will give the team time to focus on other issues.
2. *Gold Trans Am* will have a stiff carbon fiber fairing. Last year, the fairing was not stiff enough and flexed during testing, causing pieces to break. This year, the fairing has additional carbon fiber and Nomex honeycomb ribs to increase the vehicle's structural integrity.
3. *Gold Trans Am* will be a safe and stable vehicle. *Gold Trans Am* will be stiffer than *Llama Del Rey*, and the rollbar will be more reinforced than *Llama Del Rey*'s, which will be beneficial in the event of a crash.
4. *Gold Trans Am*'s fairing will be manufactured following the successful two-part male mold process that was used on *Llama Del Rey*.

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Part 1: Design

1 Objective

For the 2015-2016 season, the Olin College Human Powered Vehicle team iterated on the previous year's effective tricycle design with the goals of increasing ease of fabrication and improving safety features. Compared to previous years, the team had fewer skilled machinists, so special care was taken to replace complex custom parts with simpler designs and off-the-shelf components. To address problems with the previous year's design, the team focused on improving fairing stiffness and designing an improved chain routing system.

2 Background

With the increase in national and global sustainability and environmental initiatives, there has been a growth in interest toward forms of transportation that are more environmentally friendly than the standard automobile. While bicycles are convenient and economical, they lack the safety features and speed offered by automobiles. Faired recumbent bicycles offer increased rider protection and power efficiency unparalleled by traditional bicycles, making them a good alternative to modern automobiles.

3 Prior Work and Background Research

Much of the inspiration for *Gold Trans Am* comes from the Olin College Human Powered Vehicle Team's 2015 vehicle, *Llama Del Rey*.[1] The key feature of this vehicle is its use of a multi-cavity composite layup process. This process utilizes two male molds which are laid up separately and later joined to form a stiff composite monocoque with an effective rollover protection system. The ribs laid up in the vehicle fairing are a new design, but due to the effectiveness of the multi-cavity layup process and the simplicity of fabrication due to the reduction of internal layups, the team used a very similar process to create the fairing for *Gold Trans Am*. The team also used *Llama Del Rey's* sub-frame design as a starting point for the design of the same components on *Gold Trans Am*. Additionally, the team used many of the test and analysis results performed in developing and evaluating *Llama Del Rey* to aid in the testing and analysis of *Gold Trans Am.*

The team also used the Rickey Horwitz Design Primer to aid in the steering geometry and drivetrain design[2]. The team used the primer to help decide on a drivetrain configuration and used the specific definitions of steering geometry components to optimize our own handling characteristics. The team's mold manufacturing process was inspired by those utilized by the University of Toronto's Human Powered Vehicle Team[3]. Additionally, the team drew inspiration from many previous Olin College vehicles that competed in the ASME Human Powered Vehicles Challenge.

4 Organizational Timeline

Gold Trans Am was designed and constructed entirely in the spring semester. The team began by designing the vehicle, focusing on iterating and improving the previous year's vehicle by analyzing its flaws. The team also used tools developed in previous years, such as a measuring jig. During February and early March, the team focused on the construction of the vehicle. In late March and early April, the team tested the vehicle and shipped it to competition. An overview of the process is shown below.

<table>
<tr><th rowspan="2">Week Of</th><th colspan="2">Design</th><th colspan="2">Manufacturing</th><th rowspan="2">Testing</th></tr>
<tr><th>Fairing</th><th>Drivetrain</th><th>Fairing</th><th>Drivetrain</th></tr>
<tr><td>18-Jan</td><td rowspan="2">Shape</td><td rowspan="2">Frame</td><td></td><td></td><td></td></tr>
<tr><td>25-Jan</td><td></td><td></td><td>Epoxy Release</td></tr>
<tr><td>1-Feb</td><td>Ribs</td><td rowspan="3">Drivetrain</td><td></td><td></td><td></td></tr>
<tr><td>8-Feb</td><td></td><td>Mold Making</td><td></td><td>Window</td></tr>
<tr><td>15-Feb</td><td></td><td rowspan="3">Composite Lay-Up</td><td></td><td rowspan="2">Frame Lightening</td></tr>
<tr><td>22-Feb</td><td></td><td rowspan="3">Steering</td><td></td></tr>
<tr><td>29-Feb</td><td></td><td rowspan="3">Machining</td><td></td></tr>
<tr><td>7-Mar</td><td></td><td>Foam Removal</td><td></td></tr>
<tr><td>14-Mar</td><td></td><td></td><td>Hatches</td><td></td></tr>
<tr><td>21-Mar</td><td></td><td></td><td>Window</td><td>Assembly</td><td>RPS Test</td></tr>
<tr><td>28-Mar</td><td></td><td></td><td colspan="2">System Integration</td><td></td></tr>
<tr><td>4-Apr</td><td></td><td></td><td></td><td>Spare Parts</td><td>Full Vehicle</td></tr>
<tr><td>11-Apr</td><td colspan="5">Ship Vehicle</td></tr>
<tr><td>18-Apr</td><td colspan="5">Competition</td></tr>
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Table 1: Organizational Timeline.

5 Design Specifications

A weighted quality matrix was used to translate the team's aspirations into a set of design specifications. In the matrix, aspirations are located on the left, and capabilities are listed along the top. The body contains the values indicating the strength of correlations between the two to allow the capabilities to be prioritized.

Areas of prioritization include roll bar strength, responsive handling, and minimal construction time. From these prioritizations and the ASME HPVC rules, a list of concrete, measurable design specifications was created to guide the design of *Gold Trans Am*.

Specification	Target
Roll bar vertical strength	600 lbf
Roll bar lateral strength	300 lbf
Turning radius	2.5 m
Weight	75 lbs
Drivetrain efficiency	95%
Repair time	20 min
Vehicle construction time	250 hrs
Vehicle width	32 in
Vehicle length	95 in
Drag coefficent (CdA)	0.04
Cost of materials	2500 USD
Rider changeover time	60 sec
Field of View	180°
Number of parts	50
Stopping distance (15 mph)	20 ft
Cargo area can fit grocery bag	True
Responsive handling	True
Rider safey harness present	True
No sharp edges near rider	True
Aesthetically pleasing vehicle	True

Table 2: Vehicle Specifications.

		Roll Bar Strength and Coverage	Responsive Handling	Construction Time	Drivetrain Efficiency	Repair Time for Minor Failure	Weight	Field of View	Number of Machined Parts	Turning Radius	Mean Time Between Failures	Shell Volume	Aerodynamic Drag	Cost	Aesthetically Pleasing Vehicle	Explores Innovative HPV Techniques
Ensures rider safety	5	9	3					3		3	2				2	
Ease of manufacturing	4			9					7					3		
Reliable	4	9				9			3		9					
Quickly repairable	4			2		9			3							
Time spent manufactring	4			9		1					2					
Capable of high speeds	4		3		9		9	3			1					
Visibility	4							9								
Easily controlled	4		9		2					9						
Minimal aerodynamic drag	4												9			
Accelerates quickly	4				9		9						3			
Rides well in all conditions	3		6							3						
Aesthetically pleasing	3														9	
Low cost	3			2					3					9		
Easy to enter and exit	3											3				
Can fit through college doors	3											9				
Can be pushed backwards	2				1											
Advances the state of HPV technology	2															9
All riders can operate vehicle	2	3	3									9				
Can carry groceries	2											1				
Absolute Importance		87	87	86	82	76	72	63	61	60	58	56	48	39	37	18
Relative Importance (Sums to 100)		10	10	10	9	8	8	7	6	6	6	5	5	4	3	3
Target		600	8	250	95	20	75	180	50	2.5	20	1.8	0.04	2500	7	4
Units		lbs	1-10	hrs	%	mins	lbs	deg	#	m	hrs	m^3	m^2	USD	1-10	1-10

Table 3: Quality Function Deployment Matrix.

6 Structural Monocoque Fairing

6.1 Structural Design

Gold Trans Am is built as a ribbed carbon fiber monocoque fairing with aluminum sub-frames. The fairing is structural and acts as the rollover protection system, shielding and keeping the rider safe in the event of a crash. The main body of the vehicle is composed of two layers of 6K twill weave carbon fiber. Ribs are composed of 0.5” thick Nomex honeycomb with shredded carbon fiber, glass microsphere, and epoxy filling in the edges.

The team decided on this design paradigm after considering ideas in a weighted design matrix. The most important criteria to the team, which were given the highest weight, focused on rider safety and manufacturing time for machined parts. Many of the current team members have composites experience, but this year, the team did not have as many skilled designers and machinists. Additionally, the team lacked a skilled welder. Therefore, the team wanted to focus on designs that would take less machining resources and take into account that composites manufacturing is an area of strength. The team built a carbon fiber monocoque for last year’s vehicle and was therefore familiar with that fabrication process.

Category	Weight	Carbon Monocoque, Roll Bar	Carbon Monocoque, Steel Roll bar	Steel Frame, Structural Fairing	Steel Frame, Non-Structural Fairing
Rider Safety	1	10	9	7	2
Vehicle Weight	0.7	8	6	0	2
Repairability	0.4	0	2	4	4
Interface Complexity	0.6	5	0	3	3
Schedule Complexity	0.6	2	0	4	4
Time-Composites	0.6	2	2	4	6
Time-Welding	1	4	2	0	0
Time-Machining	1	4	2	0	0
Fairing Quality	0.8	8	8	6	4
Total		35.4	25.6	20	16

Table 4: Structure Design Matrix.

From this analysis, it was decided that a carbon fiber monocoque with an integrated rollover protection system was again the best design choice to fit the criteria set out by the team. Although the process is time consuming, it minimizes the time spent fabricating tubes for the frame and eliminates reliance on welding. The design has a high strength to weight ratio, helping keep overall weight down.

The monocoque structure also facilitates mounting sub-frames into the thick laminated honeycomb ribs. All the vehicle's drivetrain and steering components are mounted to the sub-frame, making sub-frame mounting to the fairing a priority. The rear wheel is supported in a separate sub frame consisting of aluminum plates mounted into the monocoque.

6.2 Aerodynamic Design

The fairing shape for *Gold Trans Am* was designed to reduce drag on the vehicle, improving vehicle efficiency and performance. After an initial model was created, the team used computational fluid dynamics software to iterate on the design and optimize the shape of the fairing for reduced drag. The results of the simulations were compared to the previous year's vehicle results, and the design of the fairing shape continued until a fairing design with suitably similar results to the aerodynamic results for the 2015 vehicle was obtained. The frontal area of the vehicle was increased slightly this year to ensure adequate ground clearance on the vehicle and to accommodate a new chain routing design. The drag coefficient for the 2016 vehicle is lower than the 2015 vehicle with a similar C_dA (coefficient of drag times area).

As with the design for *Llama*, *Gold Trans Am's* front wheels are flush with the sides of the monocoque fairing. The exposed wheels allow for rapid maintenance and repair, which has been necessary on previous vehicles. The wheel holes may negatively affect the aerodynamics of the vehicle, though cutting holes was deemed to be a better option than increasing the frontal area of the vehicle in order to fully enclose the wheels.

Gold Trans Am's fairing is also designed with an integrated composite head bubble for ease of fabrication and for aerodynamic performance. Simulation results from last year showed that without a head bubble, the fairing was substantially less aerodynamic than a design with a head bubble included. Last year's head bubble design was made from two pieces of thermoformed plastic. Due to manufacturing limitations, the two piece head bubble design was a time-intensive process as molds needed to be routed and prepared. The results were also far from optimal as the head bubble, while originally designed to be an aerodynamic shape, came out warped and, due to the two piece design, a seam ran down the middle of the head bubble, limiting rider visibility. With a composite head bubble, *Gold Trans Am* has a structural, aerodynamic shape with inlaid clear plastic panels. As the composite head bubble was added with minimal extra design and fabrication time, the change should decrease the amount of time needed to assemble the vehicle.

Other fairing designs were also considered and mainly concentrated on head bubble and hatch designs. Compared to the plastic head bubble design used on the 2015 vehicle, the fully enclosed head bubble used on *Gold Trans Am* does limit the rider's peripheral visibility to some extent while still meeting the minimum required field of view. However, this was considered to not be as important as improved forward visibility, aerodynamic performance and shorter manufacturing time.

6.3 Rollover Protection System

Gold Trans Am utilizes the fifth iteration of the integrated composite fairing rollover protection system (RPS). In past years, the RPS has consisted of a hoop of carbon fiber covering a wide foam rib with a horizontal steel support tube.

The fully composite rollover protection system used last year was validated through stiffness testing, test riding, and the rigor of competition. The team used a similar design for 2016, making improvements to the proven design. The rib cutouts were made deeper to better fit the honeycomb material, and extra carbon fiber layers were added to the rollbar. Some of the additional layers were oriented diagonally to help with torsional and flexural load cases. This year, ½" thick, ⅛" cell-width Nomex honeycomb was used as the rib and seat material. This is stronger and lighter than the polystyrene foam ribs used in previous years. Using last year's effective design, Kevlar was laid up around the rider to prevent carbon splintering in the case of catastrophic failure.

6.4 Manufacturing Process

Continuing to utilize the method perfected last year, the team used a two-cavity layup process to manufacture the fairing. This was inspired in part by the University of Toronto HPVT.[3] The process eliminated internal layups, greatly simplified manufacturing, and resulted in a stronger monocoque. Because the ribs were cut directly into the male mold, rib precision was enhanced.

Mold: The mold for the vehicle was cut on a CNC router from 3" thick polystyrene insulation foam. The slices were positioned with wood dowels and secured with epoxy to form two plugs, one for the front of the vehicle and the other for the back. Each section was wrapped in clear packing tape that acted as a release agent.

Figure 1: Wood shims placed on joining section of front plug.

Rib Filling: Instead of using expandable polyurethane foam, as the team did last year, the team used shredded carbon fiber mixed with epoxy resin and glass microspheres. This provided a structural filling material to reinforce gaps in the ribs.

Joining the Sections: A layer of Nomex honeycomb was positioned on the mating surface of the rear plug.

The two fairing halves were then aligned and bonded with epoxy. Additional layers of carbon fiber were placed between the two halves to fill small gaps between the sections. To fill larger gaps, the team put thin wood shims and a mixture of shredded carbon fiber and epoxy between the mating surfaces.

Male Mold Extraction: The team cut hatches through the center of strategically placed ribs, and the foam male mold was cut out through these hatches, as well as through the openings for the front wheels.

Sub-Frame Mounting: The front frame and rear wheel mount plates were aligned in the fairing, and holes were drilled in the necessary spots in the fairing. The sub-frame elements were attached with screws and washers.

Finishing: Filling compound was used to fill dents and imperfections in the outer surface of the shell, The fairing was then faired and painted.

Window: The window was made using 1/16 inch thick polycarbonate plastic. The plastic was heated to 160 ^{o}C and quickly molded to the shape of the fairing using the hatch and window segment cut out of the fairing. This method used less time and resources than last year's.

7 Drivetrain

The 2016 vehicle is a rear-wheel driven vehicle with an interchange near the crankset. A rear-wheel drive was chosen because the team had a large amount of experience working with a similar drive system in 2014 and 2015, and the team wanted to eliminate the need for a differential on the front wheels.

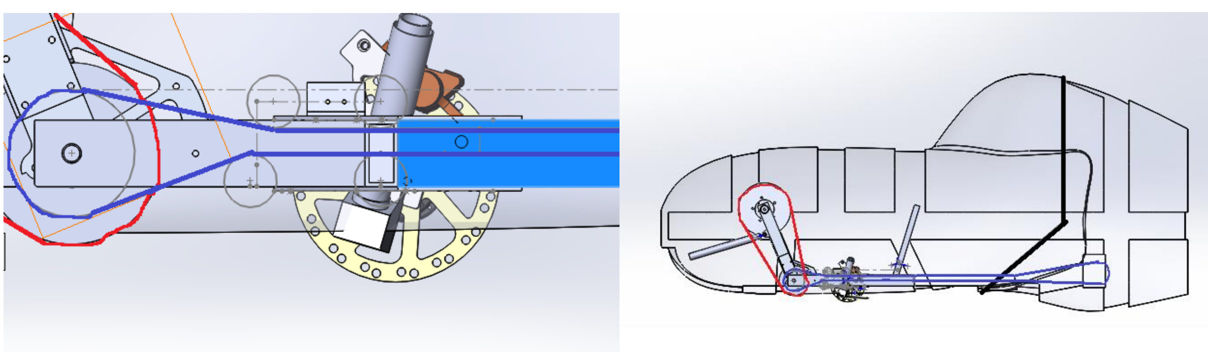


Figure 2: Chain routing arrangement. Two colors indicate two different chain lengths.

There are numerous design changes aimed at increasing manufacturability and reliability. *Gold Trans Am's* chain runs inside the fairing, avoiding the large cutouts in the fairing of the 2015 vehicle, which decreased fairing stiffness. The team designed the sub-frames around a desired chain routing arrangement, allowing the team to develop an accessible and compact solution. A traditional derailleur is mounted at the front interchange, and shifting occurs on the front chain. This design ensures that the rear chain does not change length and allows for a narrower rear wheel cavity and tapered fairing shape.

8 Sub-Frames

Components are held to the monocoque fairing with two 6061-T6 aluminum sub-frames. The front frame attaches to a large laminate rib and supports the front wheels and adjustable pedal assembly. This year, metal inserts were used to help the sub-frame attach more rigidly to the fairing. Two extra tubes were added to the frame in the aft direction, which also aid in attachment and provide a mechanism to attach idler pulleys to the frame. Additionally, an adjustable strut constructed of two telescoping tubes was designed into the swing arm structure with a quick-adjust seat-post clamp adjustment locking mechanism. The adjustable pedal system was simplified to have only two settings to facilitate quicker adjustment and simplify fabrication.

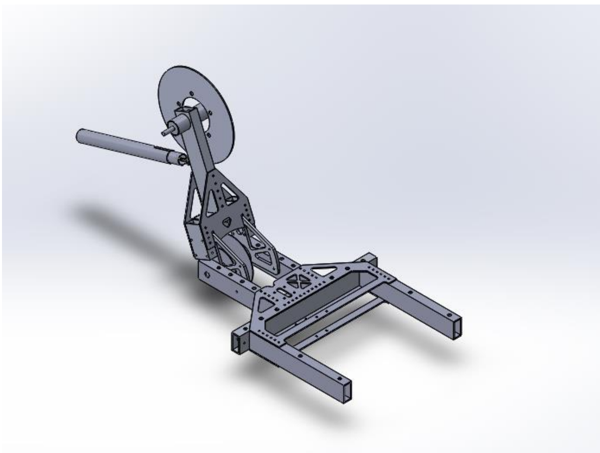


Figure 3: Front sub-frame with adjustable pedal swing arm design.

The rear wheel is supported by two separate aluminum sliding plate assemblies that are secured with clamping bolts to the fairing. One plate allows the rear wheel axle to be adjusted vertically, and the other plate allows it to be adjusted horizontally. Together, the rear wheel adjustment works to ensure that the rear wheel axle is aligned irrespective of any misalignment due to the fairing joining process.

Part 2: Analysis

9 Rollover Protection System Analysis

Objective: Ensure that the vehicle's composite rollover protection system (RPS) will protect the rider if the vehicle rolls over.

Method: Analysis was performed in SolidWorks Simulation 2015. The monocoque fairing was modeled using surface elements to determine deformation under load. The fairing ribs were modeled using an experimentally determined modulus determined in developmental testing performed last year.[1] Non-ribbed sections were modeled using experimentally determined values for two laminated layers of 6k carbon fiber twill weave. The model simplifies the composite structure as a linear and isotropic homogenous material. Although carbon fiber reinforced polymers do not generally exhibit these properties, testing demonstrated that these are reasonable assumptions for the expected loading.

Two simulations were conducted. In both cases, the fairing was fixed at the base of the seat. For the first simulation, a 600lbf load was applied at a 12^{o} angle from the vertical to the top of the fairing, right over the rollbar. The second simulation, the side load simulation, consisted of a 300lbf load applied to one side of the fairing at head level and centered around the rollbar. Both of these cases represent the inertial load of the vehicle colliding with the ground.

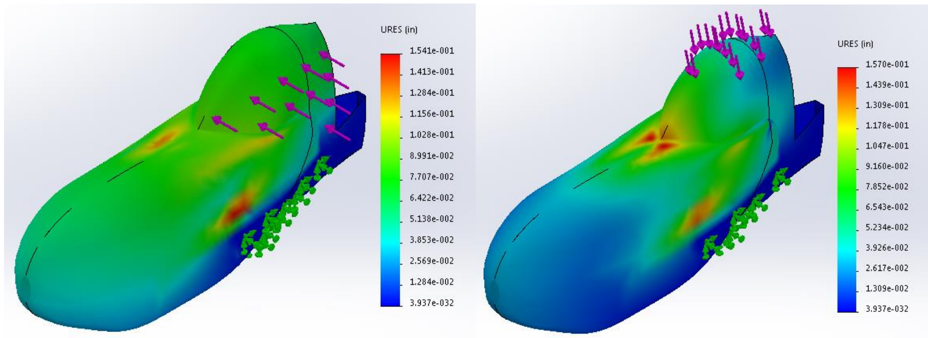


Figure 4: RPS structural analysis results.(Left) Side load case. (Right) Top load case.

Results: At the rollbar, the vehicle experiences a maximum deformation .079in and a maximum overall deformation of .157in for the vertical loading test case. During the side loading simulation, the rollbar deforms a maximum of .082in, and the whole fairing deforms a maximum of .154in. The deformation of the fairing under both loading cases is shown in Figure 4.

Impact on Design: The analysis indicates that the rollover protection system designed for *Gold Trans Am* will keep the rider safe in a crash with a significant factor of safety.

10 Aerodynamic Analysis

Objective: Use computational fluid dynamics (CFD) modeling tools to guide the iterative design of an aerodynamic vehicle.

Method: The team used CD-adapco’s STAR-CCM+ CFD to simulate the aerodynamic performance of the vehicle and compare it to past years’ vehicles, making changes in the design process based on simulation results. The simulations assume a forward vehicle speed of 30 mph and include a moving ground surface under the vehicle. Including ground effects increases the accuracy of the measurements and prevents drag coefficient inflation. In the simulation, the wheels are modeled as non-rotating bodies. This affects the results; however, the analysis performed on previous years’ vehicles used this simplification. Since the team employed the same approach as in previous years, the team was able to compare results effectively between vehicles and to simplify the process of setting up and running the simulations.

The simulation was configured with a k-ϵ turbulence model to represent the effects of turbulent flow on the vehicle. Convergence was determined to represent the effects of turbulent flows on the vehicle by monitoring the continuity and momentum residuals. Drag forces were determined by monitoring the continuity and momentum residuals and numerically integrating both the pressure and shear force gradients over the surface of the vehicle in the direction of interest. The parameter that matters most in the design of our vehicle is C_dA, which is the drag coefficient multiplied by the frontal area. C_dA is calculated from drag force. A lower C_dA value indicates a more aerodynamic shape.

Results: The final fairing shape has a C_dA value of 0.055, slightly higher than last year’s value of 0.053. Each significant iteration improved upon the results of previous iterations, obtaining a final fairing shape that fit all riders comfortably and had good aerodynamic performance.

Design	Head on F_D (N)	C_dA (m^2)	C_d	Crosswind F_D(N)
Cheryl (2014)	8.98	0.082	0.185	307
Llama Del Rey (2015)	5.83	0.053	0.089	410
2016 Fairing, Iteration 1	6.891	0.064	0.113	-
2016 Fairing, Iteration 2	6.28	0.057	0.097	-
2016 Final Fairing	6.02	0.055	0.087	447

Table 5: Aerodynamic analysis results, with comparisons to previous vehicles.

Impact on Design: The design of the fairing was an iterative process that was aided by quick feedback from the CFD simulation. Over the course of the fairing design process, several iterations were tested. For each design, streamlines on the surface were used to identify areas of high flow disruption and velocity profiles were used to find regions of the fairing that caused large flow speed reductions.

Through the design process, the team found effective design changes to implement in the vehicle. Compared to previous designs, the 2016 fairing shape has a more gradual taper at the aft of the vehicle, helping to reduce turbulent flow at the trailing edge. Additionally, the integrated head bubble design helped reduce the drag on this vehicle. Even though the frontal area of the vehicle was increased from 0.594 square meters to 0.624 square meters, there was a minimal increase in C_dA. Since increasing frontal area of the vehicle addressed chain routing and ground clearance issues from last year while increasing rider comfort, the team determined that a slightly larger C_dA was an acceptable tradeoff. Simulated fluid velocity profiles for *Gold Trans Am* and *Llama Del Rey* are shown in Figure 6. Note the thinner column of disturbed air behind *Gold Trans Am* as compared to *Llama Del Rey*.

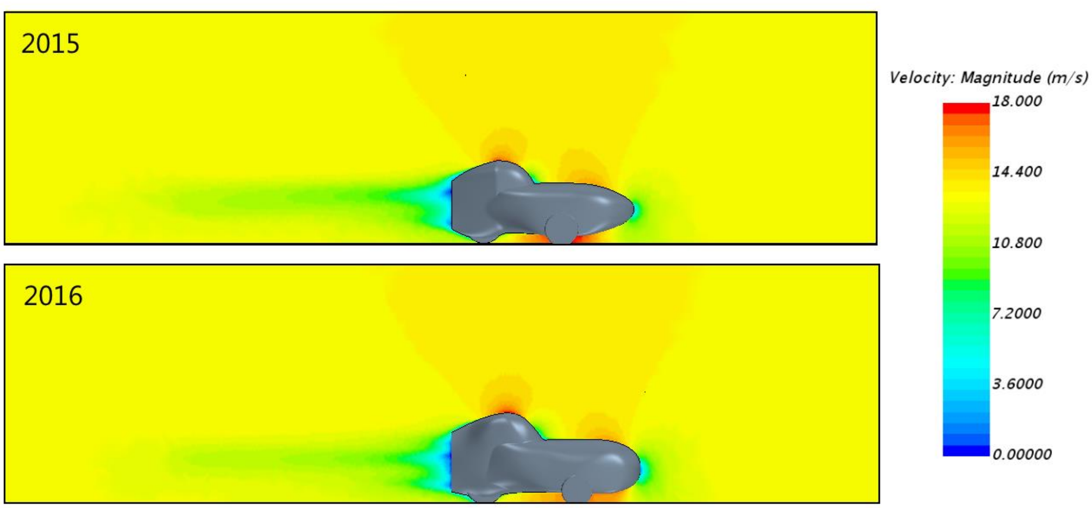


Figure 5: Head on aerodynamic simulation results. Colored regions indicate reduced flow velocity in vehicle wake.

Additional simulations were performed to determine *Gold Trans Am's* performance in a crosswind. A 10 mph crosswind was added to the 30 mph frontal air velocity of the head-on drag simulations. In a 10 mph crosswind, *Gold Trans Am* is resisted by 447 N of sideways drag force, greater than *Llama Del Rey's* 410 N. This increase is due to *Gold Trans Am's* higher side profile.

In a tricycle, a crosswind moment is reacted against the outboard wheels and the lateral friction force on the ground. Given these results, the team is confident that the vehicle will not roll over or break traction due to a 10 mph cross-wind. The team has not had issues in the past with handling during a crosswind, so the team believes that increased crosswind drag will have negligible effects on race performance. The crosswind flow profiles are shown in Figure 7.

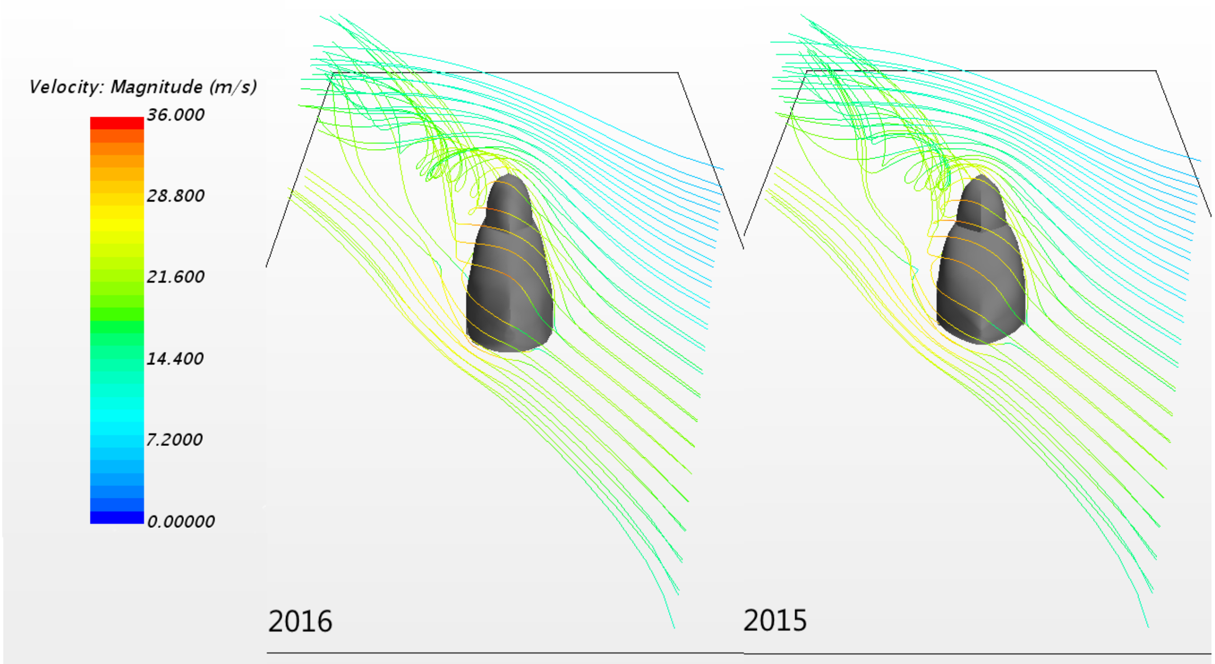


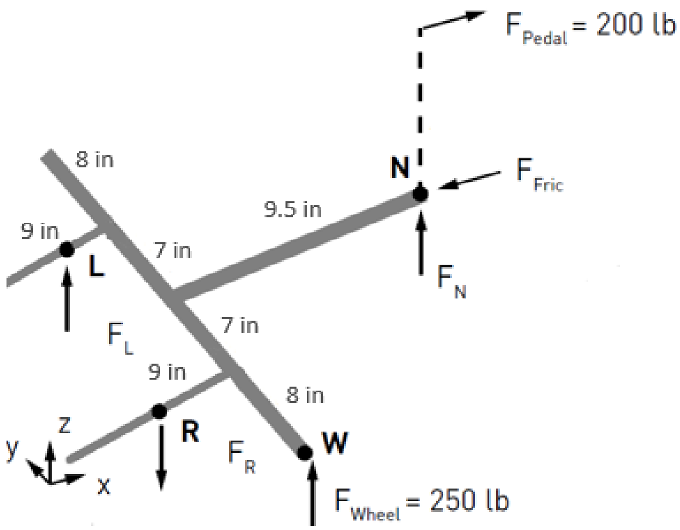
Figure 6: Crosswind simulation results. Colored regions indicate reduced flow velocity.

11 Structural Analyses

11.1 Front Frame

Objective: Ensure that the front frame and its connection to the monocoque will not fail under expected loads.

Method: To perform testing, the frame was geometrically simplified for analysis. At points L, R, and N, the frame is held into the vehicle by bolts. F_{RIC}, the frictional force, is generated by the normal force of a polyurethane rubber between the aluminum frame and the monocoque. Fewer mount points were used in this model to create a statically determinate system which resulted in overestimates of the loads at the mount points.



$$
\begin{aligned}
F_L &= 133 \text{ lbf}\\
F_R &= 402 \text{ lbf}\\
F_N &= 19 \text{ lbf}\\
F_{FRIC} &= 200 \text{ lbf}
\end{aligned}
$$

Figure 7: Front frame structural model.

A worst-case scenario was analyzed which assumes that the entire weight of the vehicle is on one wheel and the entire weight of the rider is on a single pedal, with the additional assumption that the front strut is not providing a resultant force, representing a failure or lack of use of the clamping mechanism. This amounts to a 200 lbf pedaling force and 250 lbf wheel force. Resultant forces on the mounting points were determined by balancing the forces and moments of the system as shown in Figure 8.

Bolt Strength: The sub-frame is held into the vehicle with #10-32 socket head cap screws which pass through fender washers and into the carbon-honeycomb laminate and metal plates. The Nomex honeycomb has a compressive strength of 85 psi, and the bolts will be preloaded to 75% of the honeycomb's strength (63 lbs). The alloy steel socket head cap screws have a minimum rated tensile strength of 170 ksi or 3400 lbs calculated at the bolts' tensile stress area[5]. This preload, combined with the worst case bolt tensile load of 402 lbf at point F_R gives a sizable safety factor of 8.5.

Mounting Point Strength: The bolts and washers passing through the honeycomb laminate apply a bending and shear load on the floor of the monocoque. A finite element simulation was conducted in SolidWorks Simulation using the modulus and yield strength of the laminate as tested in 2015[1]. A 402 lb load representative of F_R was applied on a washer-sized region of the bottom of the monocoque. The structure was constrained at the seat. The maximum deformation was 0.1" and minimum safety factor was 2.4. This simulation, along with the additional metal plating, gives the team confidence that the monocoque will not fail at these mounting points.

Frictional Requirements: The pedaling force and moment on the front frame is counteracted in part by the frictional force on either side of a polyurethane rubber sheet (F_{RIC}). The frictional force is generated both by reaction force F_R and by the preload on the eight bolts in this area. Assuming dry Coulomb friction, a coefficient of friction of μS = 0.38 is required to oppose the pedaling force. If the coefficient of friction is lower than 0.38, the frame will shift, and the mounting bolts will be placed in shear. The expected coefficient of friction of the 60A durometer polyurethane used is approximately 0.5[10], resulting in a factor of safety (FoS) of 1.3.

Frame Strength: Hand calculations were performed on frame elements of the main sub-frame to determine the maximum normal bending stress. These calculations found that under the expected loading, the maximum bending stress is 5.7 ksi on the transverse tube, 0.55 ksi on the forward longitudinal tube, and 11 ksi on the backward longitudinal tubes. All of these values are significantly less than the 40 ksi yield strength of 6061-T6 aluminum tubing.

Finite Element Analysis: In addition to hand calculations, finite element analysis on the front frame was performed in SolidWorks simulation. The simulation found that the frame had a minimum factor of safety of 2.85, with most of the frame having a factor of safety of over 10. As shown in Figure 9, the factor of safety plot is capped at 10.

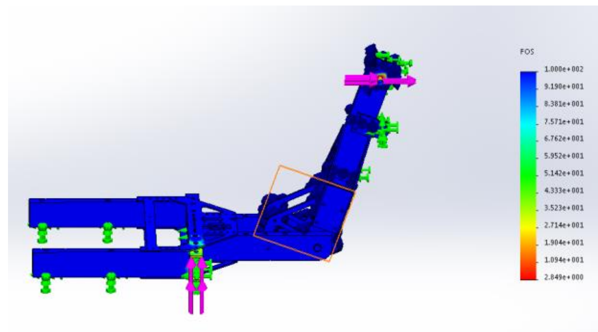


Figure 8: Front frame structural analysis results.

Impact on Design: The results of these analyses were used in several places throughout the design process. The analysis supported the choice of #10-32 fasteners as a sufficiently strong mounting option. The thickness of the monocoque underneath the frame was influenced by analysis results. The urethane rubber under the frame was chosen to have an acceptably high coefficient of friction. Frame strength analysis suggested that while most of the frame may be overbuilt, the areas around the embedded nuts are weak points and should not be aggressively lightened. The analysis did suggest that more bolt holes should be added to the forward frame tubes in order to provide the necessary preloading force to result in a 200 lbf friction force. The initial design had six holes, and this was increased to eight to ensure that the necessary friction force would be provided given a coefficient of friction of 0.5, allowing for some factor of safety.

11.2 Adjustable Pedal Components

Objective: Ensure that critical components of the adjustable pedal assembly do not fail.

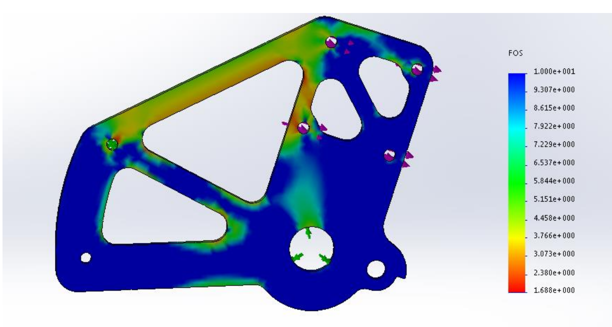


Figure 9: Adjustable pedals structural analysis results.

Model and Assumptions: In a worst-case loading scenario, a force of 200 lbf is exerted on a single pedal. Using SolidWorks simulation, finite element analysis was used to simulate the loads on the adjustable pedal swingarm plate. The plate is made out of 6061-T6 aluminum.

Results: The plate was analyzed in Figure 10 and found to have a minimum factor of safety of 1.69. The safety margin suggests that even in an extreme loading case, the part will not fail.

Impact on Design: The analysis performed by the team suggested that the thinnest element in the part should be made thicker. The team changed the part before fabrication to ensure that it would not fail under the expected loading case.

11.3 Pedal Adjustment Pins

Objective: Ensure that the pedal adjustment pin holes will not be damaged by load exerted by the rider on the pedals.

Method: The moment on the adjustable pedals swingarm was calculated assuming a worst case scenario of 200 lbf load on the pedals with no load on the swingarm strut. The bearing force on the tubes at the pins in Figure 11 was determined using hand calculations. Note that the swingarm is in a typical rider position and not oriented vertically. As designed, there is no swingarm position that is perfectly vertical.

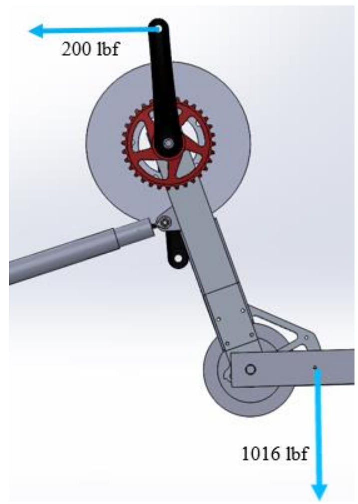


Figure 10: Adjustable pedals structural model.

Results: The calculations found that the bearing stress on each tube wall was 10.8 ksi, much lower than the 6061-T6 Aluminum yield strength of 40 ksi and yielding a factor of safety of over 3.5.

Impact on Design: Due to the high factor of safety at the pin holes, that portion of the tubes will not need to be reinforced, and the team is confident that the holes will not deform under expected loading cases.

11.4 Rear Wheel Mounting

Objective: Ensure that the adjustable rear wheel mounting assembly will not fail while under load in competition use cases.

Loading: The final weight of *Gold Trans Am* with a rider is estimated to be approximately 250 lbs with 60% of this weight on the rear wheel. Using SolidWorks Simulation, a 150 lbf load was placed on the shaft of the rear wheel assembly. This shaft is held in place by two alignment adjustment plates which are clamped in place and bolted to the fairing (Figure 12**)**.

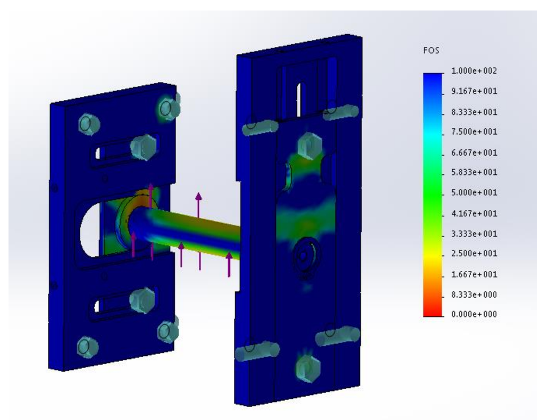


Figure 11: Rear wheel assembly structural analysis results.

Clamping Screws: The weight of the vehicle is transferred to the monocoque through friction between the clamped plates. The ¼-20 socket head clamping screws used in the design have a minimum rated tensile strength of 170 ksi. Assuming dry Coulomb friction and a coefficient of friction of 0.2, with the four bolts preloaded to 75% of their yield strength, the rear wheel is secured with a 3200 lbf frictional force, leading to a factor of safety of 21.

12 Other Analyses

12.1 Speed and Gearing Analysis

Objective: Ensure that the vehicle's gearing allows the rider to reach maximum performance and accelerate quickly from a stop.

Method: The team used a dynamic analysis of the vehicle system to determine the maximum vehicle speed given a specified power input and aerodynamic drag[4]. From rider power data collected by the team in 2014, the team estimates that a powerful rider can sustain 300 W in a sprint. To select gear ratios, the team used a spreadsheet to calculate vehicle speed for given sprocket sizes and rider cadences. The team used an interchange of 30 teeth, a rear wheel sprocket of 20 teeth, and a drive wheel diameter of 20 inches for the analysis.

Shifting Sprockets			Speed (mph)		
Speed	Teeth	Total Ratio	70 rpm Cadence	90 rpm Cadence	110 rpm Cadence
1	34	1.76	7.35	9.45	11.55
2	24	2.5	10.41	13.39	16.36
3	22	2.73	11.36	14.6	17.85
4	20	3	12.49	16.06	19.63
5	18	3.33	13.88	17.85	21.81
6	16	3.75	15.62	20.08	24.54
7	14	4.29	17.85	22.05	28.05

Table 6: Gearing and speeds for 40 tooth chainring.

Shifting Sprockets			Speed (mph)		
Speed	Teeth	Total Ratio	70 rpm Cadence	90 rpm Cadence	110 rpm Cadence
1	34	2.29	9.55	14.17	17.32
2	24	3.25	13.54	17.4	21.27
3	22	3.54	14.77	18.99	23.2
4	20	3.9	16.24	20.88	25.52
5	18	4.33	18.05	23.2	28.36
6	16	4.88	20.3	26.11	31.91
7	14	5.57	23.2	29.83	36.46

Table 7: Gearing and speeds for 52 tooth chainring.

Results: The results show that by using two chainrings, the vehicle can have a configuration that allows for high acceleration and another that allows for a higher top speed.

Impact on Design: The team decided to use two chainring combinations, one for the endurance race event and a different one for the sprint race event, to yield the best balance between top speed and acceleration. For the endurance event, the team selected a 40 tooth chainring. Using a 30 tooth interchange and a 14-34 cassette, a rider will be able to accelerate quickly out of stops and be able to navigate obstacles more easily at lower vehicle speeds. For the sprint portion of the race, vehicle top speed is of high importance, so the team opted to go for a 52 tooth chainring, a large, commercially available size. This allows the vehicle to reach a top speed of 36.46 mph.

13 Cost Analysis

Both the cost of producing *Gold Trans Am* as presented and the expected cost of a three year run are shown in the table below.

Comparison to Specification: *Gold Trans Am's* material cost of $3910 is higher than the original specification of $2500. The team based the original specification off of last year's spendings. However, last year the team started with a lot of leftover materials. In contrast, this year the team had to purchase almost all the materials used. Additionally there was an increase in the cost of off-the-shelf machined parts since the team bought more of them to reduce fabrication time.

Category	Cost	Subtotal	Totals
Material Costs			
Commercial Off-the-Shelf Parts		$955.00	
Steering System	$170.00		
Drivetrain System	$500.00		
Brake System	$200.00		
Fastening Hardware	$85.00		
Metal and Plastic Stock		$215.00	
Aluminum Rectangle Tubing	$25.00		
Aluminum Stock	$190.00		
Composites and Supplies		$2,740.00	
Composite Fabrics	$770.00		
Ribs and Fillers	$500.00		
Epoxy System	$420.00		
Polystyrene Foam	$600.00		
Vacuum Bagging Supplies	$450.00		
Single Vehicle Material Cost			$3,910.00
Production Vehicle Cost (With 40% Bulk Material Discount)			$2,346.00
Monthly Production Costs			
Labor per Vehicle		$2,600.00	
Machinist	$1,400.00		
Composite Technician	$1,000.00		
Assembly Technician	$200.00		
Overhead per Month		$1,650.00	
Rent	$1,200.00		
Utilities	$400.00		
Machine Upkeep	$50.00		
Total Monthly Production Costs (10 vehicles per month)			$27,650.00

Production Line Capital Investment			
CNC Router	$18,000.00		
CNC Mill	$45,000.00		
Lathe	$25,000.00		
Water Jet Machine	$80,000.00		
Welder	$4,000.00		
Vacuum Pump	$350.00		
Hand Power Tools	$1,200.00		
Other Hand Tools	$400.00		
Total Capital Investment			$173,950.00

36 Month 360 Vehicle Production Run			
Total Cost			$2,013,910.00

Table 8: Cost analysis results.

14 Product Lifecycle/CO_2 Analysis

The environmental cost of producing *Gold Trans Am* was calculated using the data from the table below. The calculated data includes the embodied energy, which is the sum of all the energy used to create each individual component, as well as the total carbon dioxide emissions resulting from the production of the vehicle.

Environmental Impact			
Materials	**Mass Used (kg)**	**Embodied Energy (MJ)**	**CO2 Footprint (kg)**
Carbon Fiber 3K Twill, 50"	16.99	39,080	2922
Carbon Fiber Quad Weave	1.586	7,293	554.9
Kevlar	0.5097	117.2	6.626
Batting, Pillow Forms (D9 Foam, Polyester)	2.458	13.52	0.9709
Peel-Ply Release Fabric (Nylon)	96.15	10,770	759.6
Epoxy (2gal 635 Resin + 3-1 Hardener 85oz)	27	306	189
1" Paintbrushes	3.4	193.6	11.46
US Composites Expandable Foam	0.34	44.2	1.962
Glass Microspheres	0.1134	3.062	0.1667
Popsicle Sticks	0.0149	0.05588	-0.01639
Vacuum Film (Stretchlon)	3.54	460.2	20.43
Vacuum Tape (25' rolls)	2.58	270.9	10.19
Aramid Nomex Honeycomb (3lb per cubic foot, .5"x2'x4' per sheet)	2.039	244.7	10.26
Wood	0.412	1.545	-0.4532

Window Plastic (1/16" thick, 24"x48", clear)	2.832	240.7	16.99
Wooden Dowel (1" diameter, 24" length)	0.207	0.7763	-0.2277
Sandpaper	0.45	15.3	0.8325
Vacuum Oil	1.36	36.72	4.455
Blue Foam (3"x4'x8' per sheet)	56.25	5456	195.2
Clay	0.907	8.163	1.224
Nitrile Gloves	1.36	141.4	5.331
Plastic Cup (5oz, clear)	0.907	87.98	3.156
A Grade Clear Packaging Tape (2" diameter, 330" length)	0.907	87.07	5.714
HDX Clear Plastic Sheet (100'x100')	4.5	504	35.78
Metal Aluminum	22.26	534.2	40.96
Spray Adhesive (10.25oz cans)	0.907	74.37	2.177
Plaster of Paris Tub Molding Material	3.63	24.32	0.8349
Electricity (Shopbot)	N/A	1073	279.8
Electricity (Other Manufacturing)	N/A	509.5	132.9
Total		67,590	5,213

Table 9: Product lifecycle analysis results.

This analysis was done primarily using CES EduPack 2007. Amounts of materials used were calculated or estimated based on receipts and records. The mass of materials was calculated using measured masses when available; otherwise, densities from product websites were used. The CES EduPack software gave ranges, and precise compositions of many materials are company secrets so approximations had to be made for material composition, embodied energy, and carbon dioxide footprints. Throughout the process, every attempt was made to remain as accurate as possible. For example, when calculating the embodied energy and carbon dioxide footprint of paintbrushes, the brushes were broken into a wooden handle, a steel alloy ferrule, and synthetic polymer bristles. The relative weights of these three components were used to calculate the environmental impact of the brush. Anything with wood has a negative impact, though overall, that had a negligible influence on the total.

Electricity calculations were done for the major parts of the manufacturing process. It was assumed that the ShopBot CNC Router had a four horsepower (HP) spindle and that the vacuum that was run throughout the process used six HP. These machines were run for approximately 40 hours. Likewise, it was assumed that 50 hours of other machining consisted of 40 hours of milling using a three HP mill and 10 hours of turning using a seven HP lathe. These values were based on average values for similar, and sometimes even identical, machines found online[5, 6, 7, 8].

Not included in the environmental analysis were the environmental impact of shipping the vehicle to competition, the garbage created by using these materials (including having materials shipped, packaging materials, disposal of packaging, and disposal of materials), heating the composites bay while doing layups, the electricity used to power the vacuum, lights used while working, electricity used to power hand tools such as a Sawzall and electric sander, and electricity used in the manufacturing and shipping of stock parts that the team purchased. These were not included because of the limited resources for learning about product lifecycles and because of the impossibility of some record keeping (for example, the lights used to light our space are used simultaneously by other teams).

Furthermore, the end of the vehicle's life must be considered. We propose that none of our vehicle should go to waste. Any internal pieces that can be reused in another vehicle should be. Remaining metal pieces that are no longer viable in their current form should be taken to a metal scrap yard to be sold or recycled for future projects. The reprocessing of the metals would be small and will be ignored. The rubber from the tires would be used for children's playground turf. This processing, too, will be ignored because of the small amount of material. Finally, if the fairing is still intact, it can be recycled. There are carbon fiber recycling plants that could transform the fairing into new products. The environmental impact of the recycling process has not been calculated, but it would be much smaller than the impact of disposing of it.

Given the many assumptions made, the estimated values for embodied energy (67,590 MJ) and carbon dioxide footprint (5,213 kg) are not very precise. However, we believe these to be fairly representative of the resources that were used in manufacturing our vehicle. Were we to build vehicles on a larger scale, we might be able to reduce our footprint per vehicle.

Part 3: Testing

15 Performance Testing

15.1 Rollover Protection System Testing

Objective: Ensure that *Gold Trans Am's* composite monocoque is sufficiently strong to protect the rider in the event of a serious crash.

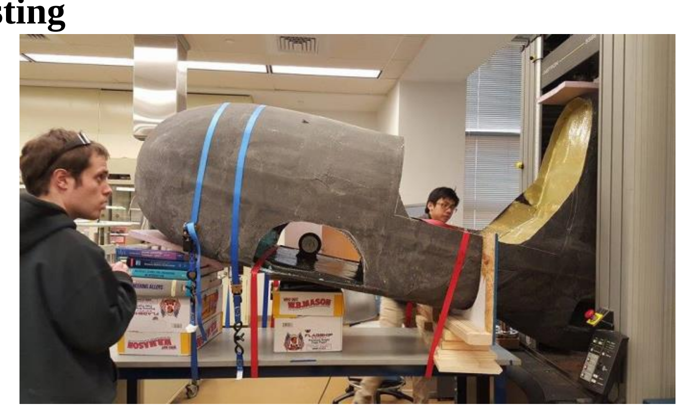


Figure 12: RPS top load test setup.

Top Load

Method: The monocoque was subjected to a 600 lbf top load applied at the rider's head at 12° from vertical. The load was applied using an Instron mechanical tester. The vehicle was constrained by straps at the seat; the region of the monocoque directly opposing the applied load was not supported.

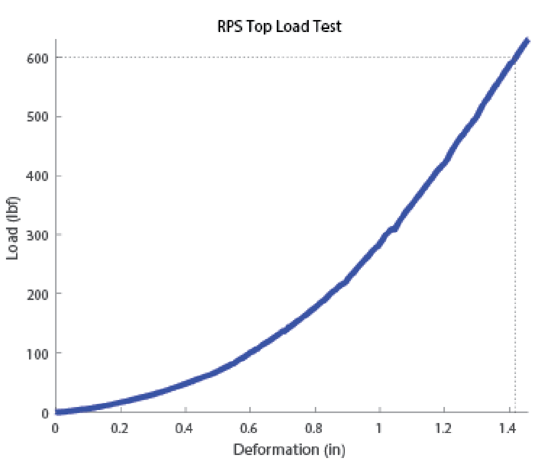


Figure 13: RPS top load force-deflection curve.

The compressive load was applied at a rate of 0.393 in/min through a piece of polystyrene foam, distributing the load across an approximately 10 in^2 region. After reaching a load of 630 lbf, 5% above the required specification, the load was held and the fairing was then inspected for damage and deformation was measured. The load was relaxed and the shell was once again measured and inspected for damage.

Results: At a load of 600 lbf, a deformation of 1.42 in was measured across the monocoque. After unloading the shell, the fairing returned back to its original size, indicating that all deformation was elastic. The approximately linear shape of the load-deformation curve also suggests that all deformation was elastic. Inspection of the fairing found no cracked fibers, delamination, or any other damage. The test was repeated twice with no significant change in deformation.

Side Load Method: The rollover protection system was tested by applying a 300 lbf side load at a rider shoulder height. The monocoque was cantilevered from a steel structure clamped to the base of the vehicle seat. No part of the vehicle other than the seat was supported.

Figure 14: RPS side load test setup.

Two team members weighing a combined 320 lb stood on the vehicle and deformation was measured. The load was applied gradually, and the monocoque was monitored for damage throughout the duration of the test. The two team members were fully supported by the side of the vehicle. After measurement and inspection of the monocoque, the load was removed.

Results: Under the 320 lb load, 0.51 in of deformation was measured at the shoulder. After the monocoque was unloaded, no plastic deformation was measured. Inspection of the monocoque following the test found no damage.

15.2 Visibility Testing

Objective: Ensure that *Gold Trans Am's* field of vision allows for safe operation and meets the design specification.

Method: One team member of average size sat in the fairing (without the main hatch on) and identified points on the ground that she could see around the vehicle while turning her head and remaining inside the fairing. Only one test was necessary as booster seats will be used to equalize the height of riders' eye levels.

Results: The rider's field of view without the main hatch was determined to be approximately 340°. The data from the test was used to create a visibility map (Figure 16).

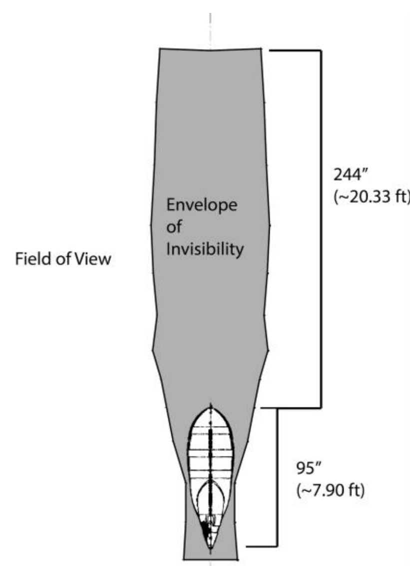


Figure 15: Visibility test results.

Comparison to Specifications: The rider's 340° field of view exceeds that of the 180° design specification and that of *Llama Del Rey's* (200° with the main hatch on). However, we intend to have a main hatch that encloses the rider. A wide enough window will be installed in the hatch to meet the 180° field of view design specification.

Impact on Design: *Gold Trans Am* with the main hatch on will have at least a 180° field of view. Despite that, there will still be a blind spot behind the rider. Thus, mirrors and other visibility features and accessories will be added to further increase the field of vision.

15.3 Rider Changeover Testing

Objective: Ensure that riders can enter the vehicle, put on the hatch, and be ready to ride in a reasonable amount of time.

Method: For one change in riders, the total time elapsed for entering and exiting the vehicle was measured via stopwatch. One rider got out, another rider got in, and the hatch was replaced.

Results & Comparison to Specifications: The total time elapsed during the vehicle changeover process was 25 seconds for the one change in riders. This is well under the 60 second specification that the team allotted for rider switching during the endurance race. It is noted that the addition of seat belt adjustment and pedal adjustment will add some time to the entire process, but the team is confident that these can be done in less than 36 seconds with the help of other teammates.

Impact on Design: The team found that the wider hatch improved the ease of entering and exiting the vehicle, and the hatch will remain wide in future designs.

15.4 Weight Testing

Objective: Test how the weight of *Gold Trans Am* compares to the design specification and identify areas of opportunity for weight reduction.

Method: All parts of the vehicle already completed were individually weighed and tabulated. The weights of unfinished parts were estimated using previous years' measurements and the team's knowledge of changes made.

Results & Error Analysis: The total vehicle weight is estimated at 84.3 lbs (Table 10). Note that components were weighed in the granularity presented in the table and were not broken down to the smallest possible unit. The scale used was recently calibrated, but had a resolution of 0.5 lbs. Across the 12 weighings done, there is the possibility for stackup error of ±3 lbs. Because the actual weight for the

Subsystem	Component	Weight (lbs)	
Fairing	Shell	46.5	52.5
	Main Hatch	4.5	
	Back Hatch	1.5	
Front Frame	Frame	2.5	19.8
	Adjustable Pedals	6.5	
	Knuckles & Steering	6.8	
	Wheels	4	
Rear Wheel	Shaft & Mount Plates	0.5	3
	Wheel	2.5	
Misc.	Chain	4	9
	Seatbelt	2	
	Hardware	3	
Total			84.3

Table 10: Weight test results.

frame components are estimated from last year's vehicle, an additional error margin of ±2 lbs was added.

Comparison to Design Specifications: Testing indicates that the vehicle weight will be 84.3 ± 5 lbs, slightly above the 75 lb specification.

Impact on Design: Weight testing indicates that the best opportunities for weight reduction are in the front frame assembly, specifically the adjustable pedals and the steering. Lightening these assemblies will be investigated before competition. While the fairing shell represents more than half of the vehicle weight, it serves as the RPS which is very important, so any decrease must be carefully considered. However, the fairing is 19.5 lbs heavier than last year's fairing. In the future, the weight of the fairing might be decreased while making sure safety remains the top priority.

16 Developmental Testing

16.1 Fairing Size Verification

Objective: Ensure *Gold Trans Am's* fairing is large enough to comfortably and safely fit at least six members of the team.


Figure 16: Fairing fit verification setup.

Method: A recumbent rider jig created last year was used to test fairing fit. Foam cutouts of cross sections of the vehicle in the shoulder, knee, and toe areas were created. The cutouts were attached to the jig and riders sat in the jig and pedaled to verify fairing size.

Results and Impact on Design: It was determined that all riders could comfortably fit into the vehicle, giving the green light for fairing manufacturing to continue.

16.2 Frame Lightening and Carbon Fiber Support

Objective: Save weight without sacrificing structural integrity in the frame.

Method: The team reinforced lightened aluminum tubing with carbon fiber to experiment with a potential lightening technique. A mill was used to create pockets in a length of ⅛ inch thick 6061-T6 Aluminum 2x1 rectangle tubing, similar to the tubing used for the 2015 vehicle frame and to the tubing used for *Gold Trans Am*. Carbon fiber was laid up around these pockets. Once cured, the sample was tested and compared to a piece of unlightened aluminum tubing of the same length.

Figure 17: Aluminum tubing carbon fiber reinforcement test pieces.

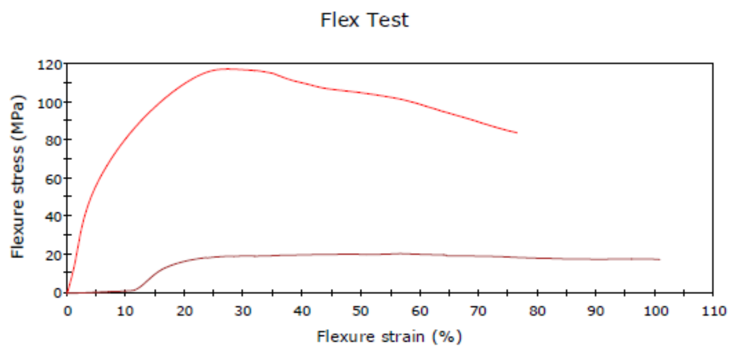


Figure 18: Three-point bending test results. Red curve represents regular aluminum test piece, brown curve represents carbon fiber-aluminum test piece.

Results and Impact on Design: The testing results, in Figure 20, showed that when a tube was significantly lightened, the carbon fiber added to support the tube could not compensate for the lack of structural support. The process was also time consuming, and saved only an estimated 0.15 pounds per 1 foot length of tube. Consequently, the process was not adopted for use on the 2016 vehicle, but the team will consider exploring and refining the process for potential use in future years.

16.3 3D Printed Steering

Objective: Save weight and machining time using 3D printed steering parts.

Method: In order to save time on machining a complex steering part and to save a little weight, the team experimented with 3D printing parts on a MarkForged Mark One 3D printer. This printer has the ability to print in nylon, supplemented by fiberglass, carbon, or Kevlar fibers. The team used fiberglass fibers to test two different steering parts, corresponding right and left steering knuckles.

Figure 19: 3D printed steering knuckle.

Results and Impact on Design: The team tested the design by replacing the steering parts on *Llama Del Rey* with the 3D printed parts. During the testing, when a team member put their full weight on the vehicle, one of the parts broke, failing at the transition layer between fiberglass and nylon. In order to fix this problem and still get the benefits of using this manufacturing method, the team redesigned the part to have a longer fiber section in the section of the part that is inserted into the frame tube. By 3D printing this part, the team saves 6-10 hours of manufacturing time and 0.2 pounds per knuckle.

Figure 20: 3D printed steering knuckle with failure along nylon-fiber boundary layer.

16.4 Mold Release Testing

Objective: Determine the best mold release method to improve ease of foam removal and also improve fairing finish.

Method: Three test pieces of carbon fiber were laid up - one on untreated foam, one on foam treated with Turtle Wax Rubbing Compound (a coating compound researched as a potential mold release candidate), and one on foam with clear plastic tape completely covering the surface. This was done to simulate how our fairing is laid up on a male plug and has to be removed after.

Results: Of the three test pieces, the test piece laid up on untreated foam performed worst. The foam was difficult to remove from the test piece, and a layer of foam had tightly adhered to the epoxy and test piece. The rubbing compound worked well for foam removal. However, the bond between the compound and test piece was strong and could not be separated, leaving a matte white layer on much of the test piece. The test piece laid up on taped foam performed the best; the foam was easily removed from the test piece, and the test piece had a smooth, high-gloss finish.

Figure 21: Mold release testing (no epoxy, rubbing compound, tape).

Impact on Design: Last year, the team used a mold release compound similar to the rubbing compound, which resulted in a rough internal finish with sections of hardened mold release compound tightly adhered to the fairing. Based off the results of this test, tape is an ideal mold release and produces a fairing with a clean finish and makes the foam removal process easier.

The time required to apply the tape onto the mold is comparable to that of applying mold release compound, as the mold release requires multiple coatings and dry time in between coats.

16.5 Rib Gap Filling Testing

Objective: Determine the best method for filling in gaps between the fairing and honeycomb ribs.

Method: Six types of rib, each with a different type of filling material, were subjected to a four point bend test to determine the modulus of elasticity of each sample. The American Society for Testing and Materials recommends a four point bend test for determining the stiffness of sandwich laminates.[7] Three specimens of each type of rib were tested.

The ribs were created by taking a one inch piece of Nomex honeycomb, cutting it in half, and creating a sandwich panel sample with a quarter inch gap in between the two honeycomb pieces. The sandwich panels were vacuum bagged and left to cure. The team compared the effectiveness of the following fillers: no filler material, epoxy, epoxy with glass microspheres, shredded carbon fiber and epoxy, shredded carbon fiber and epoxy with glass microspheres, and expandable polyurethane foam.

For the purpose of calculating a useful modulus for analysis, the samples were assumed to be linear and isotropic. Beam bending equations were used to estimate the modulus of elasticity (E) from the applied Force (F) and the measured deformation (v). Parameters in the formula include the x-coordinate of the left center support (a), the x-coordinate of the right center support (b), the distance between the outer supports (L), and the bending moment area of the section (I).

$$E = -\frac{Fa}{6LvI}\left(aL^2 + bL^2 - 2a^3 - b^3 - ba^2\right)$$

All test samples were 1.25 inches wide, with the exception of the test pieces without any filler. These samples pinched inwards when vacuum bagged. Since the test was designed to compare the best filler material as opposed to test the RPS stiffness, this was not considered to be a significant issue. Modulus is a useful test metric as the data from these tests can be used for analysis of deformation at load.

Results: The six rib sections were each tested and the modulus of elasticity was calculated for the linear region of their load-deformation curve (Figure 20). The tests were halted once the samples exhibited significant non-elastic deformation. Test samples failed through delamination.

Filler Material	Core Material	Edges Bonded	Avg. Modulus of Elasticity (GPa)	Avg. Mass (g)
No Filler	0.5 in Nomex Honeycomb	Yes	1.14	23.19
Epoxy	0.5 in Nomex Honeycomb	Yes	7.51	33.96
Epoxy with glass microspheres	0.5 in Nomex Honeycomb	Yes	1.63	32.71
Shredded Carbon Fiber and Epoxy	0.5 in Nomex Honeycomb	Yes	1.33	33.02
Shredded Carbon Fiber and Epoxy with glass microspheres	0.5 in Nomex Honeycomb	Yes	1.34	32.2
Expandable Polyurethane Foam	0.5 in Nomex Honeycomb	Yes	0.7	20.58

Table 11: Rib gap filler test results.

Statistical Analysis: Three samples were tested for each type of filler material. Error was estimated as one standard deviation from the mean, Although standard deviation deflation typically occurs with small sample counts, it is usually minor. For most of the filler material types, the test samples exhibited small deviation in modulus, validating the results.

Impact on Design: Analysis suggested that the gap filling methods used by the team would provide improvements to the RPS. Last year, the team used expandable foam to fill in gaps between ribs. Although the ribs with gap filling methods used on *Gold Trans Am* (shredded carbon fiber and epoxy, glass microspheres and epoxy, and shredded carbon fiber with glass microspheres and epoxy) are around 50% heavier than the foam-filled equivalent ribs, the moduli of elasticity are around two times higher. Considering that the team used these gap filling methods in small, targeted applications, the changes in gap filling materials were considered to be effective. To fill in larger gaps where pouring in glass microsphere filled epoxy would result in the epoxy flowing away, shredded carbon fiber and shredded carbon fiber with glass microspheres in epoxy was used. To fill in smaller gaps, the team used glass microspheres with epoxy.

Part 4: Safety

17 Design for Safety

Stable Configuration: *Gold Trans Am's* tricycle design provides for enhanced stability of a standard three-wheeled recumbent. Two wheeled designs are prone to falling over after starting forward, especially for inexperienced riders. The enhanced stability reduces the likelihood of crashes when frequently stopping and starting and allows riders of all skill levels to comfortably ride the vehicle.

Visibility to Others: The use of a bright paint color scheme and reflectors mounted at the rear of the vehicle increases *Gold Trans Am's* visibility and helps avoid unsafe situations. Visibility is an important aspect for safety, and locations for reflectors were carefully chosen to maximize their effectiveness.

Rollover Protection System: In the event of a crash, *Gold Trans Am* is able to mitigate the effect of impact on the rider. The forward section of the fairing is shaped like a leaf spring in order to reduce the impact energy during a collision. This section of the fairing is large enough that it can compress significantly without interfering with or contacting the rider. For more significant collisions, the rollover protection system that surrounds the rider is equipped to keep the rider safe. The rollbar is fully integrated into the rib structure of the fairing and will not shear or plastically deform under our expected impact forces. To prevent any contact with carbon fiber splinters in the extreme case of catastrophic failure, the rollbar has been coated with a layer of Kevlar fiber. All edges of the fairing have been rounded to minimize potential harm to the rider. The rider harness is fully attached to the rollbar to provide a sturdy mounting point and to minimize the chance of failure.

Collision Recovery: The stability of the tricycle design keeps the vehicle upright when experiencing small to moderate impacts. This attribute is vital to making *Gold Trans Am* safe during many types of collisions. Because the vehicle remains upright throughout these smaller collisions, the rider can quickly recover and pedal to a safe location rather than be stuck in harm's way. Once the rider has navigated to a safe area, the safety harness can be released quickly, allowing the rider to get out of the vehicle and out of harm's way. If the vehicle were to flip over during a collision, the rider would still be able to exit the vehicle through the large main hatch. If the rider were rendered unconscious during a collision or another circumstance during the event, first responders would be able to remove the hatch and quickly assist the rider.

Bystander Safety: This vehicle was designed and constructed to minimize collisions with bystanders. The upright nature of the vehicle allows for increased visibility which helps alert bystanders of the vehicle's presence. In the unfortunate event of a collision, the smooth, rounded surface of the fairing will minimize any injury to a bystander.

18 Hazard Analysis

Hazards accompany any mechanical system. For both the safety of the rider and the overall performance of *Gold Trans Am*, a list of possible hazards is examined and identified. The team determined potential solutions, which are presented in Table 12**.**

Likelihood	Hazard	Planned Mitigation
High	Window fogs up	NACA duct in fairing directs air flow at rider and window. An anti fog spray is used as a preventative measure.
	Rider needs to stop suddenly	Disk brakes can quickly stop the vehicle
Medium	The rider overheats	The main hatch can be removed to cool off the rider. As a preventative measure, air ducts have been incorporated.
	The rider gets dehydrated	A hydration bladder or a water bottle is available and can be stored inside the vehicle
	Flat tire	Apply brakes and replace parts at pit stop
	Broken chain	Run vehicle to pit stop and necessary repairs will be made. The chain is routed inside the vehicle, but is relatively accessible and can be easily repaired.
	Vehicle crash or rollover	Sturdy RPS, carbon fiber fairing, and extra ribbing in weaker spots protect the rider. Fairing can be opened from the inside or outside
	Loose or damaged part on vehicle	Run vehicle to pit stop and necessary repairs will be made with available tools
	Unattended vehicle rolls away	Wheel blocks and brake lock on handlebars are used
	Wet conditions on track	Riders are well-trained in Boston weather and vehicle is is very stiff, giving good road feel
	Glare interferes with rider	Rider will wear sunglasses. Main hatch is removable.
Low	Steering stuck	Disk brake quickly stops vehicle, vehicle will be repaired on spot
	Tie rod breaks	Rollover protection system protects the rider in case of loss of control. Dual disk brake can quickly stop the vehicle.
	Rider cannot fit comfortably in vehicle	Vehicle is designed for a wide range of rider sizes, with adjustable pedals

Table 12: Hazard analysis and mitigation results.

19 Safety in Manufacturing

Safety is not only a priority during vehicle use but also during the manufacturing process. When working in the machine shop, team members are mandated to tie back all hair and loose clothing and to wear long pants, closed-toed shoes, and safety glasses at all times. All team members working with metalworking tools are trained for proper use by machine shop supervisors and have passed the required safety tests set by Olin College.

When working with composite materials, safety glasses, gloves, and respiratory protection was worn to protect team members from dust, fiber, and fumes. The team makes a conscious effort to choose the safest epoxy available to limit possible inhalation and skin-contact risks. The team also works to limit particulates released by minimizing the amount of sanding and cutting of the CFRP laminate. When extracting foam from the male mold, the team decided to use minimal hot wire cutting to reduce team members’ exposure to the harmful fumes produced thusly.

During all work times, no team member is allowed to work alone, which limits the chance of injury and encourages team members to make safer decisions. In the case of an emergency, the second team member would be able to assess the situation and take the appropriate actions.

Part 5: Conclusion

20 Comparison

Analytical predictions and experimental test results are compared to the design specifications in Table 13. Quantitative targets were compared to the analytical and experimental results where appropriate.

Specification	Target	Analytical Prediction	Experimental Result	Target Met?
Roll bar vertical strength	600 lbf	> 600 lpf	630 lpf	Yes
Roll bar lateral strength	300 lbf	> 300 lpf	320 lpf	Yes
Weight	75 lbs	-	84.3 lbs +/- 5 lbs	No
Vehicle construction time	250 hrs	-	350 hrs	No
Vehicle width	32 in	30.3 in	30.3 in +/- 2 in	Yes
Vehicle length	95 in	95 in	95 in +/- 2 in	Yes
Drag coefficient (C_dA)	0.04		0.055	No
Cost of materials	2500 USD	-	3910 USD	No
Rider changeover time	60 sec	-	25 sec *	Yes
Field of View	180°	-	340° **	Yes

Table 13: Specification comparison results.

* no pedal change or seat belt
** tested without main hatch on

21 Evaluation

Below is a discussion of *Gold Trans Am's* evaluated design specifications:

- Rollover protection system analysis and testing demonstrated that the rollbar supports the required load and more with minimal deflection.
- Although final weight has yet to be determined, subsystem-level testing indicates that the vehicle will exceed the target weight as well as a result of added materials for stiffness and safety concerns.
- Final vehicle construction time has yet to be determined but is expected to be on par with last year's vehicle. The team was able to cut machining time by buying stock parts and reduce foam extraction time with a better mold release. However, with a smaller, less experienced team, the process took longer and we were not able to meet our ambitious target of 250 hours.
- Vehicle length and width were measured to be similar to the target values.
- Analytical simulations suggest a drag coefficient worse than the target value but on par with last year's vehicle. The goal was set to be ambitious, and although the specification was not met, the team is satisfied with the result.
- Accounting methods were used to keep track of material costs during the fabrication process. Due to fewer leftover materials from last year as well as an increase in ribs for fairing stiffness, we had to purchase more, resulting in an increase in expenses by 56.4%.
- The timed rider changeover was 58.3% quicker than the target time but does not account for pedal change or seat belt removal/fastening.

- The measured field of view exceeds the target value by 89%, though it was measured without the main hatch on. With the hatch on, we will ensure that it has at least a 180° field of view.

Some of the design specifications could not be evaluated at this time. These include: turning radius, drivetrain efficiency, repair time, number of parts, stopping distance, cargo area fitting grocery, responsive handling, rider safety harness, no sharp edges, and vehicle aesthetics. These qualities will be collected once the vehicle is closer to finalization. Final specification comparison will be presented in the design update presentation.

22 Recommendations

More work could be put into decreasing *Gold Trans Am's* overall weight, increasing its acceleration and improving its performance. Aluminum tubes could be lightened with a well-designed hole pattern, lowering the factor of safety. Otherwise, the tubes could be reinforced with or replaced by carbon fiber.

More time could be committed to refining the fairing design to minimize drag acting on the vehicle. More iterations of the fairing, coupled with careful study of airflow and air velocity profiles in CFD software could yield improvements in aerodynamics. CFD simulation results could also be verified by wind tunnel tests. Improved vehicle aerodynamics would allow the vehicle to be more efficient.

Electronic and electromechanical subsystems could also be installed in the vehicle to improve rider performance and facilitate data collection. For example, sensors to monitor heart rate, pedaling cadence, vehicle angle, wheel speed, and distance traveled could help the team optimize the performance of *Gold Trans Am*. Regenerative braking and anti-lock brake systems could also be explored. In order to reduce the labor needed to produce *Gold Trans Am* in a mass production setup, a reusable female mold and other fabrication fixtures could be utilized.

Many of these improvements will be pursued in future years. The team is proud to present *Gold Trans Am* at the ASME 2016 Human Powered Vehicle Challenge West.

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