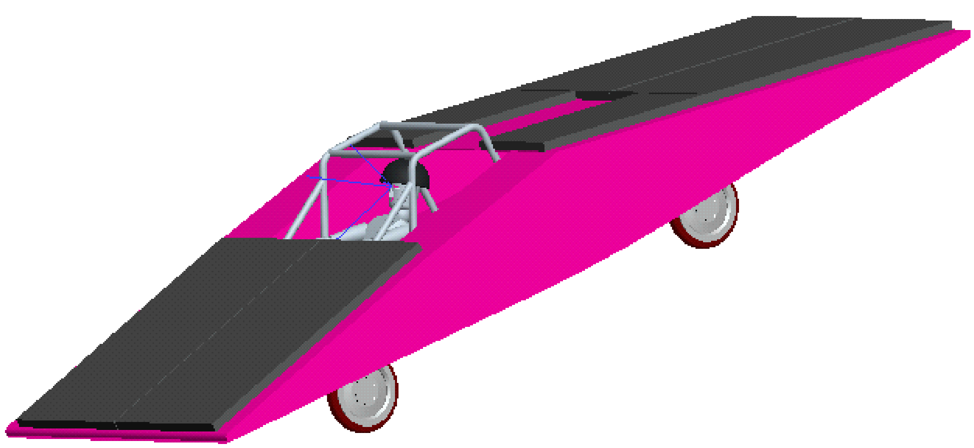
NERD GIRLS

Solar Car Design

ME 43A – Fall 2004



Allison Bedwinek
Doug Simmons
Laura Sullivan
Sheldon Low

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Executive Summary

The objective of this project was to design the shell for the Nerd Girls solar car. The shell design was to be as energy efficient as possible while adhering to all of the 2005 North American Solar Challenge Rayce regulations. The car would also need to be compatible with all other car design elements given by the Nerd Girls. Materials for the shell would need to be chosen, along with additional features including the windshield. All decisions leading up to, but not including, fabrication of a first-round shell were to be completed, and it was our goal to have the final shell ready for construction by the early 2005. This would enable the Nerd Girls team to have the full solar car completed in time for the 2005 North American Solar Car Challenge.

After extensive research of other solar vehicle designs and fluid flow over cars, several shapes for the shell and belly of the car were drawn and several ideas for the shell began to take shape. In general, we wanted to reduce the drag force on the car to decrease the amount of power drawn from the relatively weak motors, and thereby increase the life of the batteries. After reducing the angles along the profile of the car, and minimizing the surface area of the car, a preliminary design was chosen. This was then compared to the constraints given by the electrical team, and the shape was altered several times to accommodate the solar cells. The shape was no longer as fluid as was hoped, but the panels were a necessary addition. Fluid flow analysis was done along the shell of the car and features like rear wheel fairings have been added to help flow around the rear wheels.

We planned to use a custom made windshield, because we could not find a pre-fabricated windshield to fit our shell design. The specific windshield being used was to be made out of polycarbonate and its shape could be drawn to be compatible with the curve of the shell. There were a few options available for the shell material and it was decided that carbon fiber would best serve the needs of our shell. This decision was made easier by the fact that a contact was made at Secart Carbon Fiber Engineering, and we have been able to get a lot of step by step advice. Once the shell drawings are complete, they will be sent to Secart and production of the mold will begin immediately. After the mold is built, members of the Nerd Girls team will go and assist in laying out the carbon fiber within the mold. A preliminary shell is to be completed by the beginning

of February and alterations for ventilation and driver egress will be made at that time. These alterations will likely alert us to any problems within our design, and will allow us to make those necessary changes. Once it is decided that all of the problems of the design have been addressed and redesigned, the mold can be tweaked to accommodate those changes and a final car can be produced in time for the Rayce.

Our original plan was to construct a mold and have it ready in December so that the shell could go directly to the production stage. However, as our contact informed us, all that is necessary to get started is to produce detailed drawings of the final design. The mold can then be made along with the carbon fiber shell. In fact, the mold turns out to be the most labor-intensive part of the production phase, so it will be done with the help of professionals. In addition to this alteration of our initial proposal, many last minute changes needed to be made. We were only recently informed that the solar cells chosen are no longer a viable option and the large flat modules will be replaced by lighter custom built solar panels. While this allows for a much more ideal shell design, another version of the shell design will need to be quickly created, drawn, and sent off in order to ensure that the car can be assembled and ready in time for the American Solar Challenge. Finally, there were problems with the production time on the custom made windshield and so we have therefore decided to go with a prefabricated F16 windshield.

Project Goal

The goal for our design project was to design an outer shell for the Nerd Girls solar car and have it prepared for fabrication. The shell would have to enclose the driver, frame, and working parts while creating a surface for the solar panels to rest on. The main constraints that we wanted to keep in mind were the weight of the car and the drag force on the car. Flow analysis would be done on the body shape; and materials would be selected to create the lightest car possible. Another important goal was to provide adequate surface area in order to accommodate the ideal solar cell arrangement; and therefore create the most power for the car. The shell also needs to house the preexisting aluminum roll cage. Other considerations for safety and race regulations would also need to be taken into account. With these regulations in mind and an idea of the variables we could manipulate, we will prepare the shell for fabrication and be ready to compete in the 2005 North American Solar Car Challenge.

Specifications

One of the first specifications was to reduce the drag force on the car. The drag force would slow the car down and make it harder for the motors to work efficiently, increasing the total power consumed. Therefore, reducing the total drag effect on the car will allow the car to more easily maintain its forward motion, and thereby decrease the power drawn from the batteries.

Another way to increase the power to the car is to optimize the surface area and allow for the most ideal solar cell arrangement. The solar cells, which will provide all the power to the motors, were given to us by the electrical team. When we began design, we knew the approximate dimensions of the modules as well as the fact that the cells would be rigid. We also knew that we had to option of using some additional flexible cells while the car is not in motion, but the majority of the power must come from the rigid solar cells along the surface of the car.

The material for the car must be both lightweight and rigid. In order to reduce the power necessary to move the car and reduce the drag the car should be light. This will both help the car move on its own, in addition to helping it coast while the motors are not engaged. Easily moldable materials are desired because we would like to add several features to the car, while simultaneously customizing the shape for reduced drag. These features include things such as wheel fairings, ventilation, headlights and a windshield. Although there is a roll cage to keep the driver safe in case of an accident, the material should be strong and rigid to protect the driver from any other accidents that may occur.

Both the design of the shape and the size of the final body were subject to many constraints and design options. In order to actually compete and see our work in action, we must adhere to the race regulations.

- *Physical*

Before beginning on the design, our design team consulted the American Solar Challenge website to study the rules and regulations of the North American Solar

Challenge. Section 6 of the rules and regulations includes all of the rules regarding the mechanical design of the car.

The first specification of importance to the shell design was rule 6.1, which states that the maximum allowable dimensions for a single person car while moving under its own power are 5 meters long, by 1.8 meters wide, by 1.6 meters wide. It is important to note that the wheels and fairings may exceed these dimensions when turning corners.

Another section of rules considered by the design team was rule 6.11 which dealt with drag reducing devices. While the team was unsure if these devices would be implemented on the actual design, rule 6.11 explained that use of drag reducing devices is, in fact, permitted so long as the devices do not move the vehicle themselves.

Also, maximum turning radius of the car, as outlined in rule 6.15, required that the vehicle must be able to complete a U-turn within a 16 meter wide lane, without any wheels traveling outside of the lane.

- *Cockpit*

The next rule considered by the shell design team was rule 6.5, which applies to all of the cockpit regulations. Rule 6.55 states that, "The driver/passenger, when seated, must have a minimum of 15 cm of horizontal distance between his or her shoulders, hips, and feet and the car's outer body surface." Rule 6.58 also states that the driver must be able to exit the vehicle unassisted and be at a safe distance from the car within 10 seconds.

- *Ventilation*

Also, rule 6.57 requires that the solar car be equipped with an air intake vent or system so that fresh outside air is brought to the driver. At this point it is important to mention that according to rule 5.93, the batteries must be ventilated at a specific volume flow rate. While this system will be designed by the electrical team, this rule is important to the design of the shell because it requires that the system have an outtake that directs exhaust to the outside of the car.

- *Visibility*

The next section of rules directly pertaining to the design of the shell was rule 6.63, which outlines the rules regarding the forward vision of the driver when seated in the vehicle. The rule states that the driver must be able to see a point on the ground that is 8 meters in front of the most forward point on the solar car. It also states that the driver must have at least 17 degrees of vision above the horizon, and a minimum of 100 degrees left and right of the center of vision. The regulations include a section on rear vision as well; however it was omitted from this report because the electrical engineering team has provided the car with a rear view camera system which meets the terms of the race.

- *Identification*

Of little importance to the mechanical design of the shell, but necessary to comply with race regulations, is the allotment of space somewhere on the car for solar team identification. Rule 6.16 demands that the team's, "assigned number, institution name, and the Event logo…are clearly visible from a roadside vantage point." The rule continues that team sponsors or other team related graphics are permitted, so long as they are not offensive.

- *Racing*

After the mechanical rules had been studied, the team researched section 7, which provided the terms of the race itself. Rule 7.1 states that all traffic laws must be obeyed at all times, and that at no time is the solar car to exceed a maximum speed of 65 miles per hour.

- *Nerd Girls*

Once the rules of the race had been looked over, the design team began retrieving information from the entire Nerd Girls Solar Car team in order to further outline the constraints on the final shell design. The shell team was orally told that the trailer provided slightly more than 4.5 meters of length for the final shell design. Additionally, our team was provided with Pro-Engineer (See Appendix 1: Figure 1) files of a frame and chassis design. The frame was approximately 13 feet long and a little over three feet high. The approximate weight of the car without the driver was to be 700 pounds, which will be supported by the frame on four wheels. The outer diameter of each wheel, including the fully inflated tire, is approximately 18.5 inches, and each pair of wheels will have a wheelbase slightly smaller than the width of the car. Each of the rear wheels would be driven by its own motor, and the dimensions of the motors and batteries were also made accessible to the shell team so that enough space could be allotted to house and protect all of the electronics. When inquiring about the allowable budget for the shell and cockpit, the shell team was informed that while all purchases required clearance from the team supervisor, availability of funding was not going to be a large constraint. Lastly, the Nerd Girls team explained that the electrical team was working on choosing the exact solar panels to be used in the car, and that the specifications would be made available as soon as possible.

Shell Shape Research

Research began for the shell shape team by investigating the websites and designs of other teams' previous cars. Last year's North American Solar Champion team was the University of Missouri team in Rolla, Missouri. Their car, Solar Miner IV, was the fourth version in the Solar Miner family. This car provided an example of a very thin shell, shaped into a slight airfoil, with long sloping sections to minimize the slope in all directions. This website was also extremely helpful by showing the evolution of the Solar Miner series of cars. Each year, the vertical dimension of the car became thinner, and the cockpit and canopy became less obtrusive. While the overall shell became thinner, it simultaneously became less square and boxy. The upper shell began to obtain slight curve concave to the ground and an underbelly, which completed the airfoil shape. Lastly, the series of cars began as a four wheeled car without fairings and eventually became a three-wheeled vehicle with fairings on each wheel. By examining the photos and specifications of many other teams, it became clear which design elements were improved upon each year, and the similarities from one car to the next, gave invaluable information about which designs worked best (See Appendix 1: Figure 2). These similarities included thin shell designs with smooth curved underbellies. The tops were typically covered in solar cells, with equally slight curves and were shaped to make the transition from the shell curve to the windshield as seamless as possible. Also, nearly every team surrounded each of its wheels with a thin fairing. Some of the team websites, showed the car under repair during previous Rayces. This alerted us to the necessity of easily accessible and replaceable parts, as well as depicting several options for securing the shell to the frame and to itself. In addition to bringing along spare parts, many of the teams also brought extra cells with them to accelerate the charging of batteries while at a stop.

The race will run from south to north this year, as opposed to east/west in previous years. This means that the sun will move across the car from right to left. This is an important piece of knowledge since solar cell efficiency is based on the angle that sunlight hits it. A solar cell is able to extract the most energy from sunlight when the light hits the cell at exactly a 90-degree angle. Therefore, it may be advantageous to angle sections of your cells, so that they can extract maximum efficiency at all hours of the day. However, the most sunlight the earth receives is during the middle of the day when the sun is directly overhead. So it also might be advantageous to have all of your cells parallel to the ground so they can extract maximum energy during the sunniest part of the day.

Aerodynamics Research

While simultaneously browsing other teams' websites, our design team began studying the physics of aerodynamics. Our research lead us to the integral form of the conservation of momentum equation, which is displayed below:

$$\underbrace{\sum F_x - F_{o_x}}_{\substack{\text{sum of forces}\\ \text{on C.V.}}} = \underbrace{\int_V \left[\frac{\partial(\rho u_x)}{\partial t}\right] dV}_{\substack{\text{change in momentum of}\\ \text{mass contained in C.V.}\\ \text{over time}}} + \underbrace{\int_s u_x (\rho\vec{u})\cdot\vec{n}\,ds}_{\substack{\text{change in momentum}\\ \text{flux across surface of C.V.}}}$$

The left hand side of this equation includes all of the external forces on the control volume. These forces are explained in general terms in the following paragraph. One of these forces on the control volume is the force of drag, shown below:

$$Drag_f = \frac{\rho C A v^2}{2}$$

where ρ is the density of air, C is the coefficient of drag, A is the surface area of the control volume, and v is the velocity of the flow. Because one of the primary goals of the project was to reduce any forces retarding the forward motion of the vehicle, both aerodynamic drag and drag reducing devices were investigated first. The magnitude of the drag force is directly proportional to the total surface area of the control volume in contact with the flow, and the coefficient of drag of the control volume. Therefore, the smaller the surface area, the smaller the drag force on the vehicle. Minimizing surface area, however, is not enough in of itself. The coefficient of drag is also largely controlled by the size and shape of the shell. Many of the parameters which optimize the drag coefficient overlap with the variables which define pressure. There is a large retarding pressure force induced by the control volume trying to push air out of the way of the car. This force can be minimized by aiming to separate and slip through air, as opposed to pushing it out of the way. This can be accomplished by minimizing the cross sectional area normal to the flow. The thin cross section must also be complemented by smooth curves from front to back, avoiding sharp angles or sudden transitions that would disrupt streamlined flow. As flow moves around an object, a boundary layer is created along the entire no-slip exterior of the object. If the object is not streamlined, the streamlines will separate from the boundary layer, creating a pocket of turbulence and a low pressure zone, thereby inducing a large drag force. These flow disruptions can be avoided by smoothing all edges and corners and designing fillets in place of right angles. All edges, regardless of their orientation with respect to flow, will create unnecessary drag. One reason for this is that drag is a function of area touching the flow. If the amount of shell area is reduced, then the overall drag will also be reduced. A smooth streamline separation is best implemented with a sharp point at the front of the vehicle to create smooth flow separation and reduce the high frontal pressure of a stagnation point. Possibly of more importance, though, is the rear end of the vehicle. The rear of the vehicle should lead streamlines from the top and bottom of the car back toward one another as gradually as possible so that the streamlines have a smooth unification with one another behind the car. If the streamlines do not have a smooth transition, they will create vortices, which will create a vacuum behind the car, and thus increase the drag on the car. The wheels also produce drag-inducing vortices. As the wheels rotate, the air near them begins to rotate as well, and when it separates from the wheel, the air will bombard the car in different locations, and produce forces in unwanted directions. This can be avoided by building wheel fairing around each wheel, which will be designed similarly to the car, in that they will aim to separate the flow as little as possible, while simultaneously providing a smooth streamlined shape around the wheels. If fairings are not chosen, the option of using solid rims will also reduce the drag created around the wheels.

After drag, the effects of pressure were researched. Drag is always equal in magnitude and opposite in direction to the torque in the tires, therefore it might seem advantageous to incorporate some upward lift on the overall vehicle and thereby reduce the grip and torque in the tires. This can be achieved by designing wings, which are usually placed at the front of the car. However, along with lift comes a significant aerodynamic drag force. Similarly, a downward pressure might seem advantageous to increase the grip of the tires and thereby give the vehicle better handling in turns. Downward force is often achieved by utilizing a spoiler. However, similar to the wings, this force can only be achieved at the expense of aerodynamic drag. One way to increase downward pressure without inducing a large drag force is to lower the entire car, and therefore cause air underneath the car to flow faster. This will generate a lower pressure zone underneath the car, causing the car to hug the road.

One last drag-reducing device considered was a vortex generator. These devices are usually small plates, which are placed vertically on the wings of airplanes to reduce the effects of flow separation to avoid stalls. As the name implies, these extra surface geometries produce vortices, which add energy to flows by compressing the boundary layer. This increased energy reduces the chances of flow separation, and keeps larger induced vortices from forming behind the surface being studied.

Shell Shape Design

Preliminary Ideas and Considerations

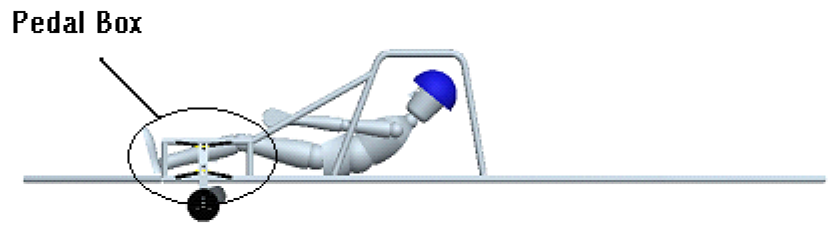
The shell was to be made up of two removable pieces: a top and a bottom. The bottom piece, referred to as the underbelly, would be permanently attached to the frame and chassis of the vehicle, while the top piece would attach to the underbelly. The ability to remove the top section is necessary for access to the inner parts of the car and for charging the panels at an optimum angle during stopping periods throughout the Rayce.

The top piece, which will be called the upper shell, can be further subdivided into three main sections. These sections include the area in front of the cockpit, the area behind the cockpit, and the area in between which directly surrounds the cockpit in the middle of the car. Based on the dimensions defined by the Rayce regulations and on the length restriction of the Nerd Girls Team trailer, the maximum black-box dimensions of the car were to be 4.5 meters long, 1.8 meters wide, and 1.6 meters tall.

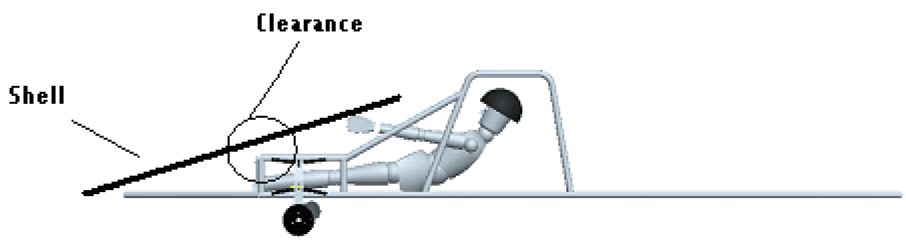
To take advantage of as much surface area as possible for solar cell placement, the full length and width of the car were to be used. The average height of the shell however, would be minimized. This will reduce the average cross sectional area normal to the airflow, decreasing flow separation and improving the aerodynamics of the vehicle. To further decrease flow separation the front point of the shell would gradually increase to the maximum height, and then gradually return to the original height at the rear of the vehicle. The gentle slope behind the canopy to the back of the car is of special importance. If the shell curves down too steeply behind the canopy then vortices can form, increasing the drag of the car. This gradual sloping of the shell would be designed to resemble a thin teardrop or an airfoil, when viewed from the side. In other words, the underbelly will be curved convex to the ground, coupled with a similar curve for the top of the shell that would be concave to the ground.

The design should also be rid of all sharp angled edges, both for the aerodynamic advantages of streamlined flow, as well as to reduce surface area normal to any flow. This also complemented the information received from the shell fabrication research, which stated that in fabrication, only bevels and fillets could be realistically constructed in place of right angles.

In addition to being aerodynamic the shell also had to be compatible with the frame. One major constraint imposed by the frame is due to a part named the 'pedal box'.



The 'pedal box' requires a minimum angle for the frontal section of the upper shell to ensure the shell clears it. This can be seen in the figure shown below:



This angle will be a major factor in our frontal cross-sectional area, which as mentioned earlier, should be kept to a minimum.

Besides fitting around the frame, the shell must also fit around the cars batteries, motors, and drive drain system. These parts will be housed in the rear of the vehicle and will require the rear section of the car to be of a certain height. This requirement will have to be balanced with aerodynamic principles mentioned earlier.

Also of concern was the aiming of the solar cells to extract the most energy from the sun. Assuming the final shell design is close to the aerodynamic shape described above; the solar cells would be nearly parallel to the ground. This would take advantage of the sunlight during the sunniest part of the day, as was stated previously.

Upper Shell

Originally, we were informed that our trailer would not fit a 5 meter long car, and that we would have to design it shorter. However, shortly after starting our initial design, we discovered that this information was false. We then changed our design to take advantage of the full 5 meters allowed.

For the design of the upper shell, there were three general designs under consideration: a front heavy design, a rear heavy design, and a symmetrical design. Because of the difference in the length of the frame and the allowable length of the entire car, there was extra shell space that could be allotted to the front of the vehicle, rear of the vehicle, or split between the two. However, regardless of the design chosen, the rear of the vehicle will still be the largest section, and will most likely hold the majority of the solar cells.

The electrical team provided us with approximate solar cell dimensions as we were beginning our initial design of the upper shell. The dimensions for the panels, in meters, are as follows: 1.37 x 0.76 (4) and 0.91 x 0.61 (2). We were also informed that cells were rigid, and would require flat space on the panel for proper mounting.

We then began investigating different panel arrangements in search of the optimal one. It soon became clear that the only way all six panels would fit, was with a front heavy shell. Two large panels would be placed on the front, with two large and two small in the back. Additionally, since each motor would be run by three of the six panels, and the motors were placed symmetrically on the left and right sides of the car; it required that each three panel set to be placed symmetrically in the same manner. The two small panels on the back section of the car were separated to leave space for the back of the canopy to slope down as gently as possible to the rear section of the car. (See Appendix 1: Figure 3)

A basic wedge-like shape was designed for the frontal and rear sections of the car. The two main concerns for the shell of the car are to hold the solar panels and to have a gradual slope in the front and in the back to avoid flow separation. The wedge shape is a good compromise between these two criteria. (See Appendix 1: Figure 3)

Originally the sides of the wedge were to be curved. This was to avoid having any type of sharp corners or flat edges, which as mentioned earlier, can increase drag. We soon realized though, that flat panel sides are much easier to fabricate, and would probably outweigh the aerodynamic advantages of a curved side. However, a fillet on all corners must remain due to fabrication requirements of flat carbon fiber panels. Also, in addition to being easier to fabricate, flat side panels gives a place for team identification to be displayed.

As shown in Appendix 1: Figure 3, a bevel was designed into the leading and trailing edges of the car. This decision was made after the electrical approached us with question of space for head and tail lights. We originally wanted the edges to come to a point, to reduce frontal cross-sectional area. However the electrical informed us they need space to mount lights within the shell itself. Therefore we added a 4 inch tall raise on the front and back edges, and curved it to be as aerodynamic as possible.

After discussing our initial design plans with our carbon fiber fabricator, we were informed that for proper molding and construction of our shell, that the front and back edges must come to a point. We stated our concern with the head and tail lights, and were told that the lights could still be mounted properly, and that the specifics would be worked out during the carbon fiber molding process.

Another question that arose was making sure the driver's feet fit in the car. Between the position of the pedals and the frontal shell section, the driver's feet could be severely cramped. To figure out how far above the frame the driver's feet would reach, the position of the pedals was determined. The driving pedals would be mounted to the frame, and would only be about six inches long. Therefore, the driver's feet would not reach past the "pedal box" on the frame; something the shell needs to clear in height anyway.

We then discovered that the dimensions of the solar panels previously given to us were in fact incorrect. The new dimensions, in meters, are as follows: 1.559 m x .798 m (4) and1.038 m x .527 m (2). This forced us to revisit our front and back section designs. Fortunately the panels were still fit on the shell, but it would require an increase in the wedge angle and height.

This height increase brought the drivers visibility into question. If the increase were too high, the shell could potentially block the driver's frontal vision. Fortunately however, the driver's visibility was not compromised by the change.

Now that the front and rear sections of the upper shell were designed, the middle section could be designed as a bridge between them. Unfortunately a windshield was still being looked for, and without those critical dimensions, nothing could be designed exactly. However some minor design parameters could still be considered. It is likely that this section will be curved, not flat like the front and back sections. This is to avoid a sharp point on the car, which could cause flow separation and an increase in drag. Also, the back of the cockpit should slope down as smoothly as possible to the back of the car, as mentioned earlier.

Eventually a custom windshield was decided upon. With the freedom to design whatever type of windshield best fits our shape, it allowed us to optimize the center section of the car in terms of aerodynamics. The section would basically curve as smoothly from the frontal wedge to the back wedge as possible, with the canopy sloping down as gently as possible to the rear, without disturbing the solar panels.

Underbelly

Next, the underbelly of the car was to be considered. Though the underbelly would need to be designed to with the wheels in mind, the bottom of the car provided many fewer protrusions and constraints on design and therefore gave the design team much more flexibility. The underbelly could be designed as a two dimensional parabolic curve, sloping slightly downward at the front of the vehicle and rising back up at the rear. The slopes were to be gradual to reduce the amount of vertical separation of streamlines as the air traveled over the body of the car. Similar to the design of the upper shell, the underbelly designs were classified as front heavy, back heavy, and symmetrical with respect to the front and rear of the vehicle. The curve would also be chosen based on the optimal conditions calculated for drag, lift, and pressure. Additionally, the underbelly would remain uniform across the width of the car; the shape will on vary with respect to the length of the vehicle.

The equations for each of these curves could be determined by designating specific points on the underbelly, plotting them on a spreadsheet, and then use a regression to output an equation. (See Appendix 1: Figure 7)

A FEMLAB analysis was performed on all of the underbelly designs. The analysis showed that the symmetrical design performed best in terms of flow and drag. This design also creates a small low pressure zone under the car which will help pull it towards the road to prevent unsafe lift at high speeds. However, after seeing the results, it became clear that one could intuitively figure that out. The symmetrical underbelly is the smoothest overall curve from front to back. The other underbelly designs contain sharper slope changes resulting in increased flow separation and overall inferior performance in comparison.

The idea of using an underbelly made of canvas, as opposed to carbon fiber, was brought up. The canvas would require wooden ribbings to hold its shape. It was thought at first that it would be lighter and cheaper to manufacture then the carbon fiber. However, according to the carbon fiber manufacturer, the weight difference would be insignificant, and the shape would be quite easy to make. Also, the carbon fiber would be stronger less prone to damage from road debris.

Other Considerations

Other aerodynamic devices such as spoilers and vortex generators were briefly considerer. Although it was decided that these additions would not enhance the performance of the car, and in the case of the spoiler would actually hinder the performance.

Wheel fairings would also be incorporated into the underbelly to reduce drag around the tires. The rack and pinion of the front wheel configuration prohibited the use of fairings which would turn with the front wheels. This meant that in order to achieve front wheel fairings, they would need to be stationary and attached to either the frame or the shell. During research of past solar cars, it was noted that some teams decided to have one long fairing on each side of the car, as opposed to separate fairings (See Appendix 1: Figure 2). This idea was discussed; however, a fairing of such length could cause difficulties for moving the car in and out of the team trailer. The center of the fairing could be scratched on the trailer ramp since it would be so close to the ground. This led the design team to opt for separate fairings for each wheel.

Since the fairings will be fixed in position they will have to be wide enough to accommodate the wheels at there maximum turning angle. The minimum turning radius designated by the rules and regulations is 8 meters. Calculations show that the wheel faring would have to be quite wide to accommodate for the turning of the wheel within the specified radius (See Appendix 1: Figure 5). To provide good flow around that width, the fairings would have to be considerably longer than desired. It seems that too much material would be required and would make the construction bulkier and more difficult. The additional length would make the fairings so long that it brings up the original problem of having one long fairing on each side of the car.

Ventilation intakes must be placed on the underbelly, to provide air for the cockpit and to cool the batteries and motors. Fans will be placed within the car to blow onto the batteries and motor so therefore just one intake can be placed near the front of the car. Of course, an outtake will also be required at back end of the car to exhaust the air. The exact placement of the intakes and outtakes will be determined during the molding of the carbon fiber.

Final Design

With all of these revisions implemented in the design, a final Pro-E drawing was generated (See Appendix 1: Figure 4). In order to get an idea of the aerodynamic properties of the shell, a flow analysis was needed. To begin, the Reynolds number needed to be calculated from the equation below:

$$\mathrm{Re} = \frac{Dv\rho}{\mu}$$

, where D is characteristic length, v is velocity of flow, ρ is the density of air, and μ is the dynamic viscosity of air. Even at speeds as low as 1 meter per second, the Reynolds dimensionless number is well above 400 and therefore the flow turbulent; so a K-E flow analysis was the appropriate strategy for investigating the flow. The flow analysis was conducted using FEMLAB, and several models and tables were created (See Appendix 1: Figure 6) as follows. It is important to note that while FEMLAB is very powerful modeling software, the complicated geometry, the slow computers used to create these models and the team's inexperience with the software combine to severely limit the modeling process. Therefore, these models are two-dimensional analyses meant only to represent the general phenomena of the flow around the car. One of the analyses was done based on the center cross section of the car including an approximate windshield and canopy design. The other analysis was done on the cross section of the car that would be on the left and right side of the canopy.

In order to perform the analysis, specific boundaries around the car needed to be designated. The dimensions of this boundary box were 4 meters high by 12 meters long and the shell was positioned in this box at its actual height above the ground and with one and a half meters in front of the leading edge. Ideally, the boundary condition dimensions should extend in all directions to the point where the flow remains undisturbed by the control volume. However, as was stated earlier, the analysis is intended strictly to give a basic idea of the flow. The boundaries around the car were defined such that the left hand boundary was the inflow with a velocity gradient equal to zero. The inflow velocity assigned to this boundary was 20 meters per second, and was chosen because it was a nice average velocity for the car. The lower boundary represents the ground and was assigned to behave according to the logarithmic wall function.

Similarly, the boundaries of the car, and the upper boundary were chosen to behave according to the logarithmic wall function. The right boundary was designated to have normal outflow. Lastly, the domain settings had to be specified. The density of air was set to be 1.29 kilograms per meter cubed, and the kinematic viscosity of air was 1.5 X 10^-5 meters squared per second.

The cross section of the center shell and canopy represents the worst flow conditions around the shell. These poor conditions are illustrated on the flow visualizations at the front of the car and at the uppermost point of the windshield and canopy. At the front of the car the pressure diagram shows a large pressure on the upper front of the shell. At the same time, flow separation on the top of the canopy causes a turbulent pocket just behind the cockpit and a low-pressure area is created. This turbulent pocket is most conspicuous on the streamline plot. The maximum velocity and pressure given by this analysis were 35.786 m/s and 264.876 Pa, respectively.

The second flow analysis represents the best flow conditions on the car. The streamlines appear to separate and return with much smoother transitions. Also, the magnitude of the pressure in front of the car is much less than the pressure in front of the canopy cross section. The maximum velocity and pressure given by this analysis were 29.868 m/s and 155.613 Pa, respectively.

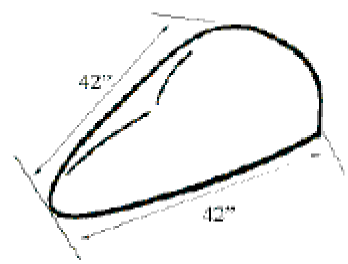
Analysis

While this final drawing represents a design that achieves all of the objectives set forth in the project goals, the design process itself presented many problems, and caused the design team to alter some of these goals. The final design succeeds in enclosing the driver, frame, and working parts, while simultaneously acting as a surface for solar cell placement. The final design also successfully meets all of the requirements of the 2005 American Solar Challenge guidelines, and it similarly manages to account for all of the constraints given by the Nerd Girls team. It is indeed prepared for fabrication, and in time to compete in the 2005 North American Solar Car Challenge. However, while the shell was designed as aerodynamically sound as possible the constraints put on this design left relatively little room for the design team to optimize the aerodynamics. First, and most importantly, the solar modules chosen by the electrical team forced a boxy and obtrusive shell design. The gentle sloping curves and streamlined body had to be sacrificed for flatter sides and sharper angles. Similarly, the frame provided difficulties to the design team. As stated previously, the pedal box required that the upper front of the shell to rise up steeply, and therefore a less than ideal frontal design was implemented. The large roll cage also requires a windshield and canopy design that is much more prominent than was hoped for. The wheelbase of the frame and the American Solar Challenge guidelines also impaired the ideal fairing design.

Alterations of final design

The revisions gone through to accommodate the solar cells turned out to be futile; the cells were changed yet again. The Nerds Girls electrical engineering team came to the conclusion late in the semester that they had chosen the incorrect solar panels. Since the solar car shell was designed to accommodate these panels, the shell must now be redesigned. This time however, it would not cause too much of a problem.

The new solar modules will be custom fabricated by SunWize out of individual solar cells purchased from SunPower Corporation. The new solar modules will cover approximately 6 to 7 square meters of surface area and weigh in at a total of 50 pounds. As the individual solar modules can be designed to whatever shape we need, the new solar car shell can take on a more fluid and aerodynamic shape. The custom windshield is no longer necessary as an F16 windshield was purchased. A 3/16" thick tinted polycarbonate windshield was purchased from FORM/TEC Plastics, Inc for approximately $750. The long, narrow shape of the F16 windshield, as seen to the right, is ideal for the low profile of the solar car.



The final shell design is in progress right now and will be completed by the end of the semester.

Construction procedures

The mold plugs are designed as solid parts in Pro/Engineer. The body will be split into multiple parts that can be machined out of foam by a large front-loaded lathe. The different pieces will be the nose, the tail, and two parts for the belly, two rear wheel fairings, and the back of the cockpit. Ideally, the number of pieces needs to be minimized so there will be less construction when connecting them back together, but the size of the parts is limited by the capability of the milling machine.

The top shell and the belly will be similar to a "clam shell" design. The top shell and the belly will meet at a point in order to "cut" through the air with the least amount of resistance. The belly will not be load bearing; the aluminum tubing frame will be supporting all of the components (batteries, motors, motor controllers, driver, and cockpit). The belly will be permanently attached to the frame. The top shell will be removable, hopefully in a single piece, if not, then in two pieces (the nose and the tail). It will mate to the belly with return flanges and locating pins. The top shell must be removable in order to angle the solar panels for maximum charging capabilities when the car is stationary. There will be a door located around the windshield and cockpit that is hinged towards the nose of the car.

By using carbon fiber, the overall weight estimate of the car will be drastically reduced, which will result in a lighter, faster, and more efficient vehicle.

Actual fabrication will begin in late January at Secart Carbon Fiber Engineering in Bethel, CT. James Seeley, CEO and founder of Secart, has been acting as a consultant to the Nerd Girls and has offered his expertise in how to design a car shell. The first step of fabrication is to create the mold. After the mold is constructed, the first version of the shell will be made. At this time in fabrication, alterations will be made to the shell for driver egress, cockpit ventilation, and fasteners. This is the best time to notice any gross errors and to take the steps to correct them. After the preliminary shell is altered appropriately, the mold will be adjusted to match the changes. The final version of the shell will come out of the adjusted mold.

Since the fabrication of the actual mold is the most labor intensive part of the process, we are very grateful to be working with Secart and for their expertise.

Division of Labor

The responsibilities of each individual team member have remained consistent, but minor adjustments have been made. Allison, in addition to being involved in all other aspects of the car as well as the shell, has been a go-between for the different teams that we need to communicate with. Our design needs to be incorporated with many different systems, including the solar cells, the roll cage, and any other systems that need to be accommodated by the shell. She has also been responsible for the getting information and vendors for the windshield. Allison was responsible for rendering all of the drawings in Pro-Engineer so that all of the groups involved and the carbon fiber company could have access to them. Laura was responsible for selecting a material and finding a viable method for future production. She found the company that we will be constructing the car with. She also assisted in calculations and decisions involving the wheel fairings. Sheldon and Doug have done a bulk of the calculations involving flow over the car. They investigated fluid flow over cars and what other team's cars are shaped like. With this in mind they designed the top shell to fit over the roll cage and frame. Once given the solar cell dimensions, they were forced to redesign and make some compromises between surface area and ideal shape for flow. They also chose a curve for the underbelly and have done FEMLAB calculations on the flow around out shell.

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Matthew Heller and Rick Colombo, Electrical Engineering Consultants to Nerd Girls

Professor Karen Panetta, Electrical Engineering Department, Nerd Girls advisor

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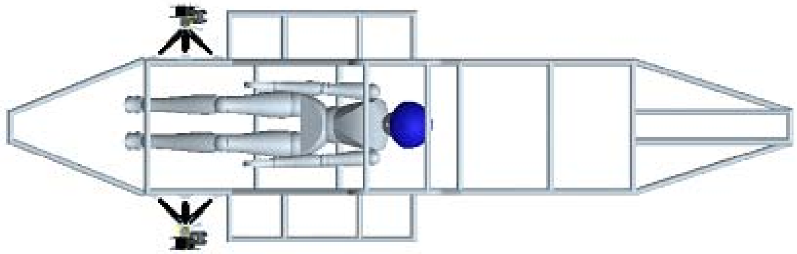
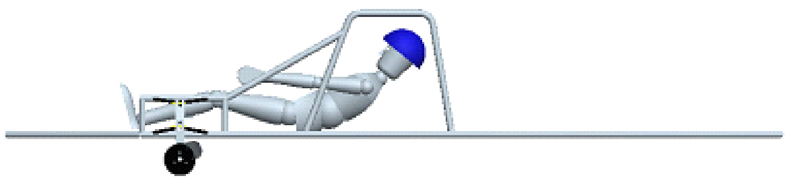
Appendix 1: Figure 1.

Frame

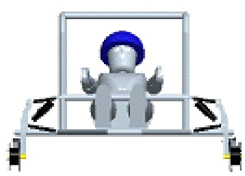
Top View



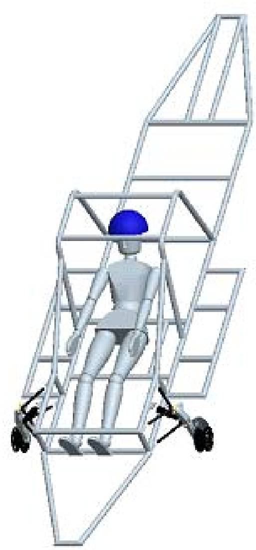
Side View



Front View



Isometric View



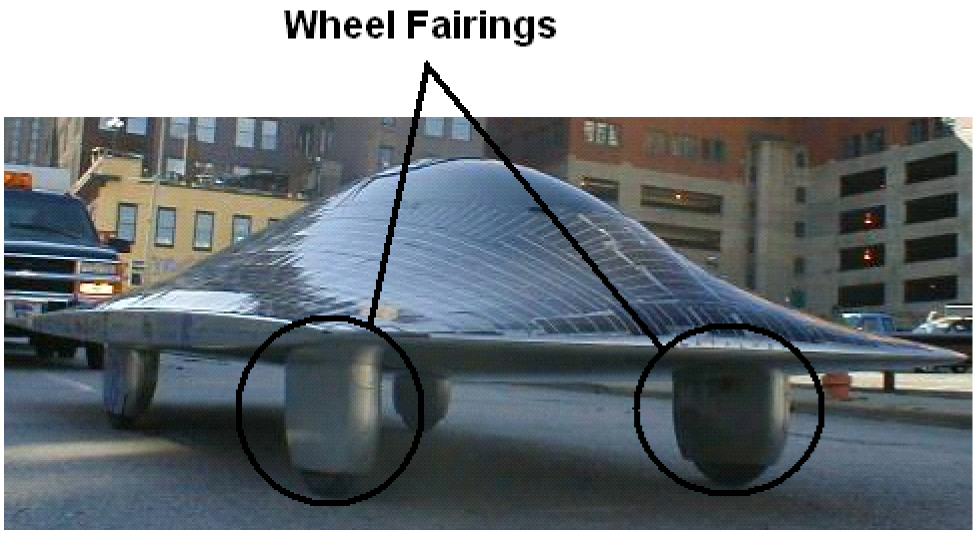
Appendix 1: Figure 2.

Missouri-Rolla Solar Car, 2003 American Solar Challenge Champion
Small Cross-Sectional Area
Slightly Curved Underbelly

Principia Solar Car: Thin and Low to Ground

Kansas State Solar Car: Streamline and Gentle Sloping Curves

Figure 2. continued



Kansas State Solar Car: Use of fairings on all four wheels

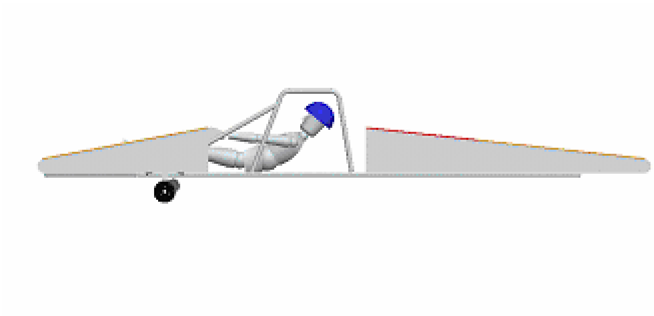
Western Michigan University Solar Car: Use of one long fairing for each side

Queens University Solar Car:
A slightly curved underbelly
Small Cross-Sectional Area
Gentle Slope from back of Canopy to back of Car

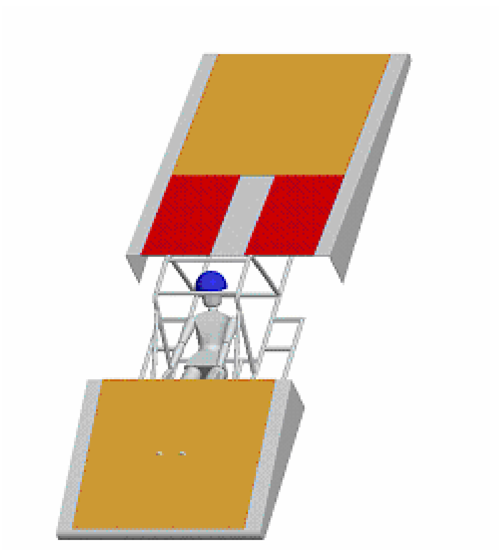
Appendix 1: Figure 3.

Initial Design Segments

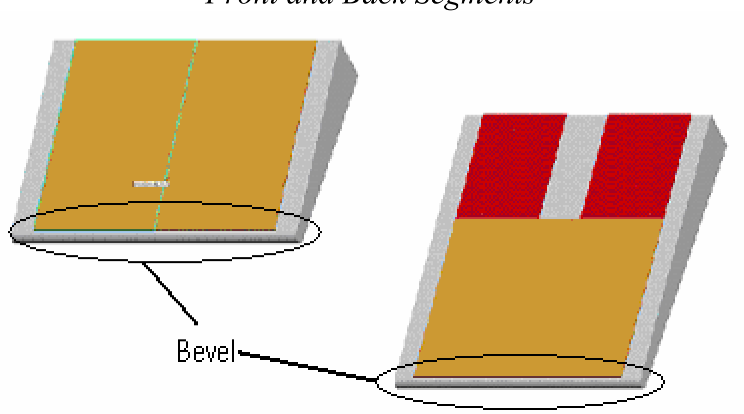
Side



Isometric



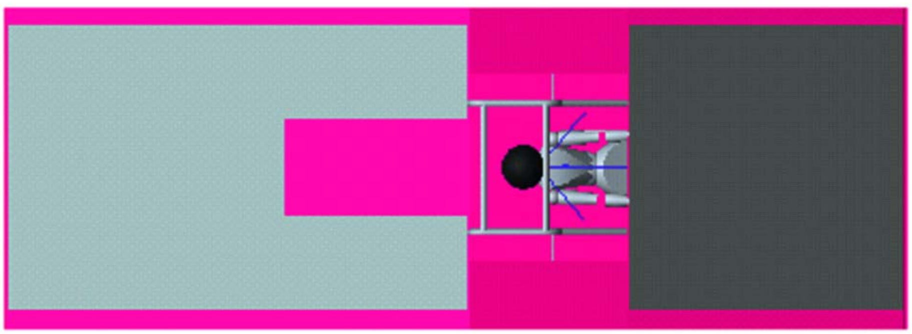
Front and Back Segments



Appendix 1: Figure 4.

Final Design of Shell

Top



Side

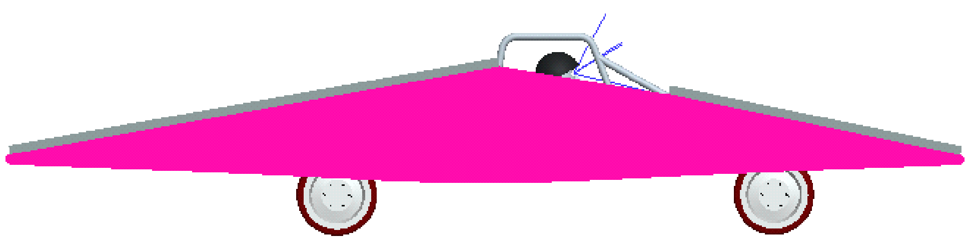
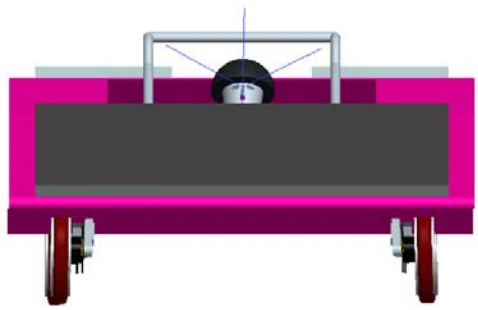
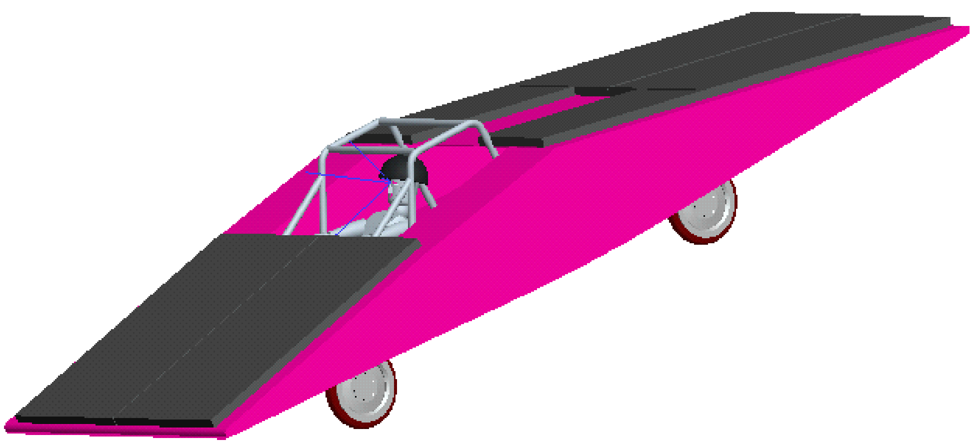


Figure 4. continued

Front



Isometric



Appendix 1: Figure 5

Wheel Fairing Calculations

Length of car (m) $L := 2.286$ length of wheel (in) $l := 18.5$

Width of car (m) $w := 1.8$

turning radius (m) $r := 8$

angle of wheel

$$\phi := \left(\frac{\pi}{2}\right) - \operatorname{atan}\left(\frac{r - w}{L}\right)$$

$$\phi = 0.353$$

inside width of faring (outside of wheel)

$$W := \sin(\phi)\cdot\left(\frac{l}{2}\right)$$

$$W = 3.2$$

inside of wheel taking width of wheel into account

$$W_i := W + 2.5\cdot\cos(\phi)$$

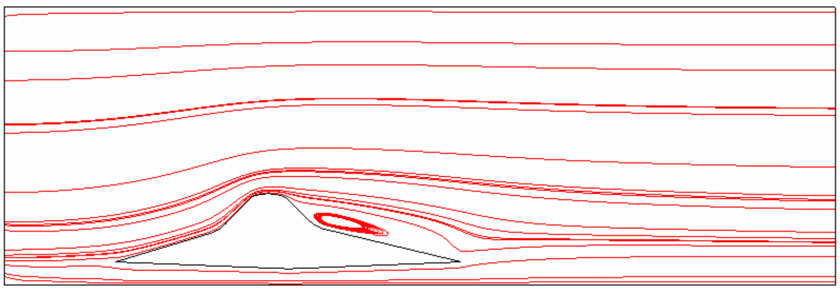
$$W_i = 5.546$$

Appendix 1: Figure 6

Flow Analysis
Center Cross-Section including Canopy

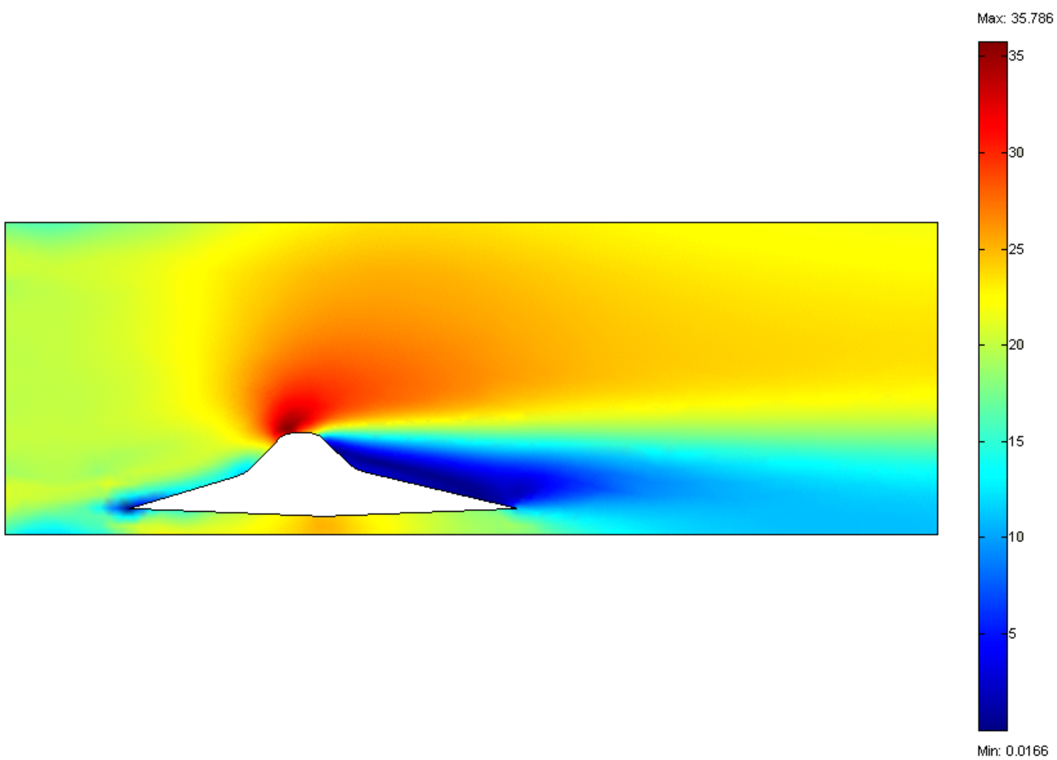
Analysis calculated at an air speed of 40 mph.
Constants:
Air Density: ρ=1.29 kg/m^3
Air Velocity: U∞= 20 m/s
Dynamic Viscosity: μ=1.5 X 10^-5 N*s/m^2

Streamlines: Air flowing from left to right



Pocket of Turbulent flow apparent behind cockpit

Velocity

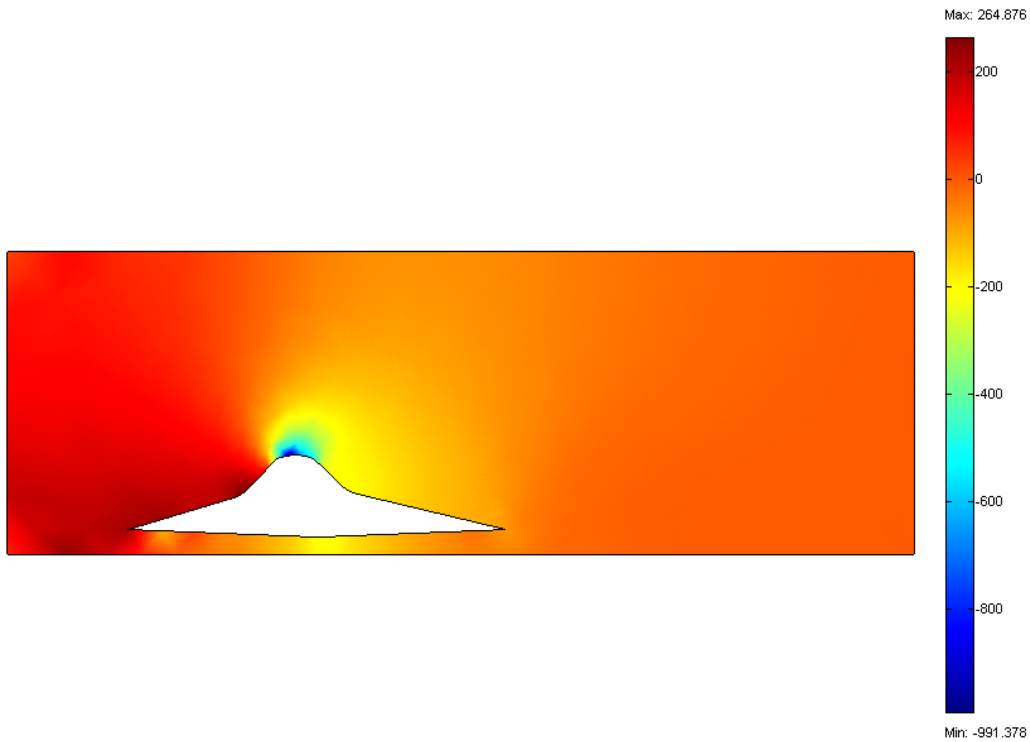


Appendix 1: Figure 6

Flow Analysis
Center Cross-Section including Canopy

Analysis calculated at an air speed of 40 mph.

Pressure



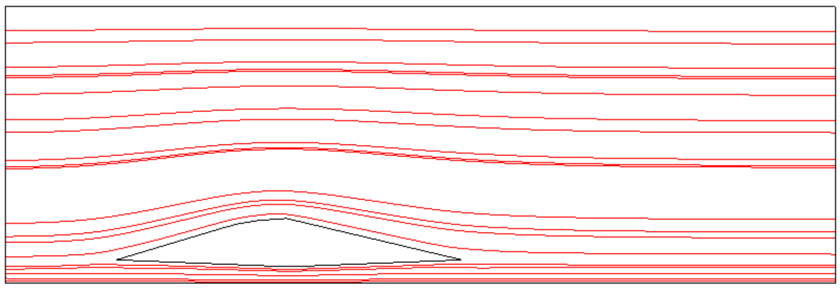
Area of high pressure at front of car

$$P_{\max} = 264.876 Pa$$
$$P_{\min} = -991.378 Pa$$
$$V_{\max} = 35.786 \, m/s$$
$$V_{\min} = 0.0166 \, m/s$$

Figure 6. continued
Flow Analysis
Side Cross-Section on either side of Canopy

Same parameters and constants as previous flow analysis.

Streamlines



Flow separates and reconnects well around contour of shell

Velocity

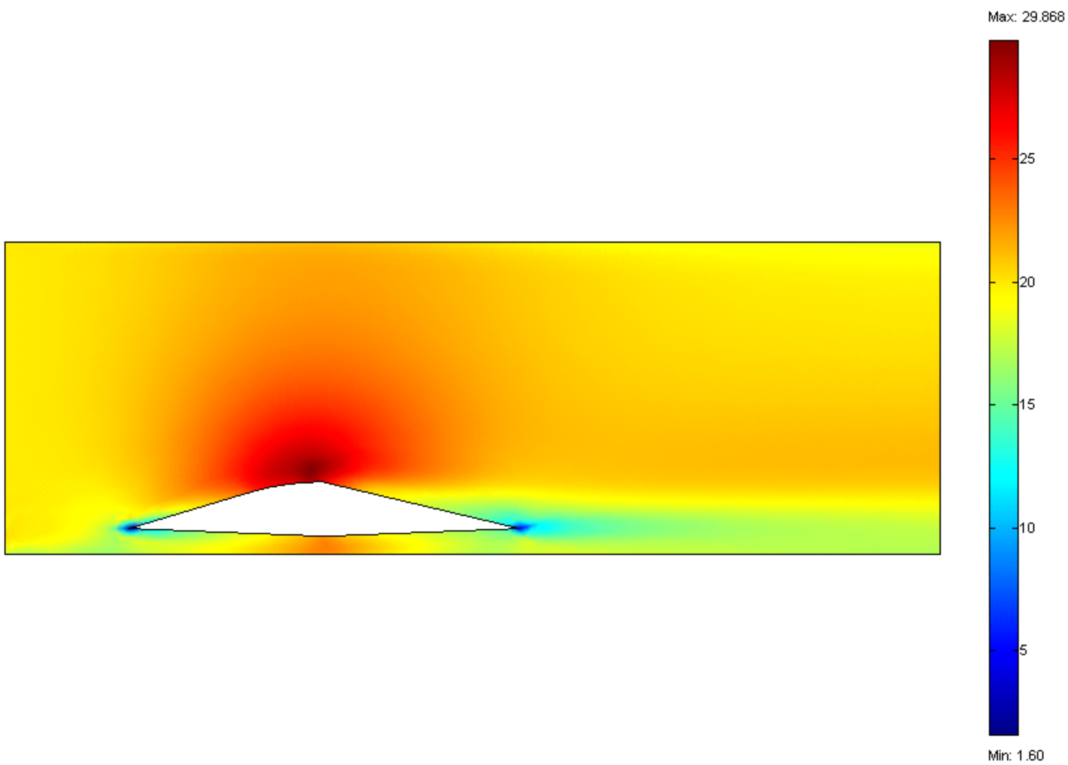
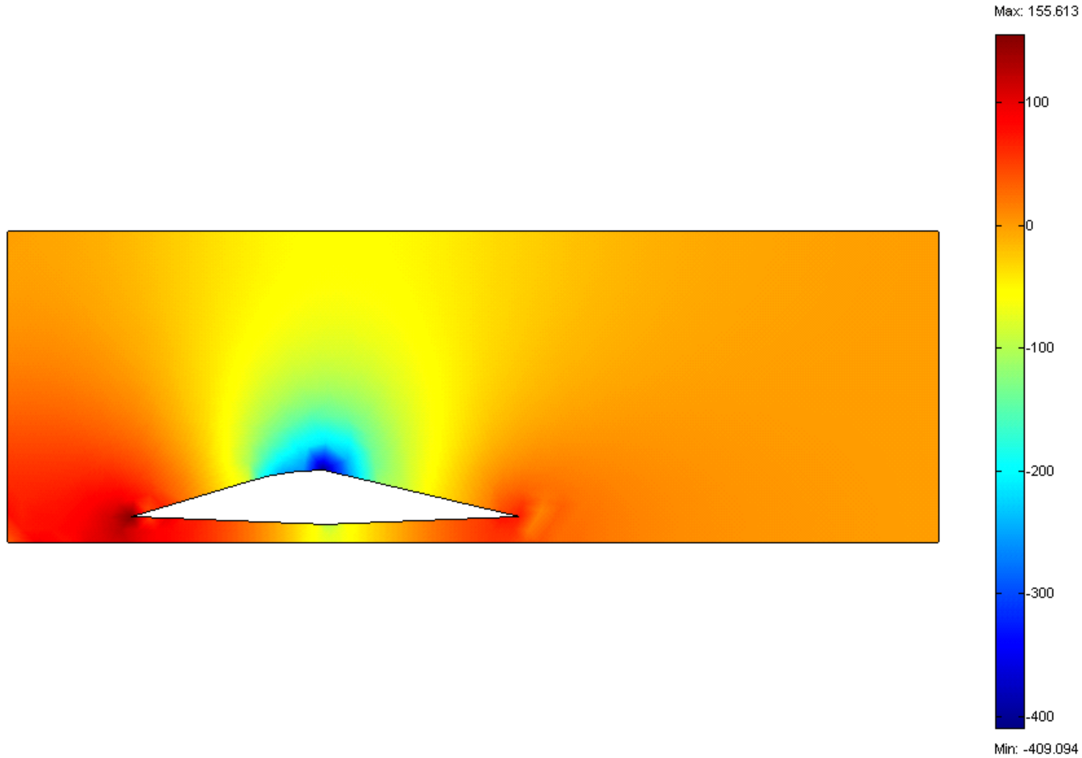


Figure 6. continued
Flow Analysis
Side Cross-Section on either side of Canopy

Same parameters and constants as previous flow analysis.

Pressure



$$P_{max} = 155.613 Pa$$
$$P_{min} = -409.094 Pa$$
$$V_{max} = 29.868 \, m/s$$
$$V_{min} = 1.6 \, m/s$$

Appendix 1: Figure 7

X is measured in meters from the front of the car.
Y is measured in meters from the bottom of the frame.

x (m)	y (m)
0	0
1.25	-0.05
2.5	-0.1
3.75	-0.05
5	0
symmetric	

x (m)	y (m)
0	0
1.25	-0.1
2.5	-0.1
3.75	-0.05
5	0
front heavy	

x (m)	y (m)
0	0
1.25	0.05
2.5	-0.1
3.75	-0.1
5	0
back heavy	

x (m)	y (m)
0	0
1.25	-0.1
2.5	-0.2
3.75	-0.1
5	0
symmetric 2	

x (m)	y (m)
0	0
1.25	-0.2
2.5	-0.2
3.75	-0.1
5	0
front heavy 2	

x (m)	y (m)
0	0
1.25	-0.1
2.5	-0.2
3.75	-0.2
5	0
back heavy 2	

Symmetric 1 was the underbelly decided upon.

Appendix 1: Figure 8

Parts List:

- 3/16 inch thick F16 Polycarbonate windshield from FORM/TEC Plastics, Inc. (http://www.racingshields.com) ~$750
- Body consulting from Secart LLC (http://www.secart.com)
- Mold plug design out of MDF and foam or 5-lb high density foam through Secart LLC
- Carbon fiber/Kevlar from Secart LLC ~>$12,000 for materials
- Labor done by Secart LLC and Nerd Girls team members
- Solar cells purchased from SunPower Corp, fabricated modules by SunWize >$15,000