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AERODYNAMICS OF SOLAR VEHICLES

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ABSTRACT

The purpose of this research project is to design the shape of a fully road worthy vehicle operating under nothing but the power of the sun. This vehicle was to meet all racing regulations of The Sunrayce and the World Solar Challenge. Because of the specific use of this vehicle, this project provides a chance to explore the aerodynamicly ideal vehicle. Little attention has to be paid to practicality. The result is a very streamlined, highly aerodynamically efficient car, that is still stable and safe.

DESIGNING A BASIC SHAPE

Governing Factors

The car is to be a highly efficient vehicle, made specifically for racing. Practicality is preserved, but not at the expense of a less competetive racing vehicle. The design is dominated by race regulations, aerodynamics needs, and restrictions due to use of solar power.

Race Regulations

"Sunrayce '93" rules and "World Solar Challenge" rules are identical in the areas pertaining to the shape of the car. The dimensions of the solar car are governed by the following rule; "All solar cars entered will have the following maximum dimensions: height=1.6 meters, width=2 meters, length=6 meters. Minimum height is 1 meter,...".[1] Furthermore, Sunrayce '93 rules stipulate the dimensions of the solar array. "The solar array, including any reflectors must at all times fit within an imaginary right rectangular parallelepiped (box) of limited size. The length of the box may not exceed 4.4 meters, the width may not exceed 2 meters, and the height may not exceed 1.6 meters. Furthermore, the product of the length and width may not exceed 8 m^2."[1] In the interest of safety there are a number of rules pertaining to visibility and driver positioning. The driver must be positioned with his head above his feet and cannot be positioned head first. His or her eyes cannot be less than 70 cm above the ground. The driver must be able to see a point on the ground 8 meters in front of the car, and must be able to see 100 degrees to either side of center.

Design Implications of Race Regulations

This race regulations lead us to the following conclusions: If the array is made narrow and long it would have the effect of lowering the cross sectional area and should reduce drag. This gives us an array 4.4 meters long and 1.8 meters wide. The car can have a minimum height of 1 meter including ground clearance. If we stay close to this minimum height, we should have a lower drag coefficient and still have plenty of internal volume. At this point we have a car 1 meter high, 1.8 meters wide, and 4.4 meters long. Next comes placement of the driver, this decision is dominated by the side vision requirement set by Sunrayce '93. The driver could be located within our box 1meter x 1.8 meters x 4.4 meters, but to achieve visibility of 100 degrees to each side of center, the area where the solar cells would be mounted would have to be sacrificed. The driver's head could be positioned in a bubble protruding above the array. This would solve the side visibility problem, but again solar cell area is sacrificed and at times the driver's head would shadow part of the solar cells. A logical solution to these problems is to position the driver in front of the solar array. The Sunrayce rules allow for a maximum length of 6 meters; we have allocated 4.4 meters of that for the solar array. This leaves 1.6 meters to place the driver in and achieve the specified side visibility. Because there can be no head first positioning for safety reasons, the full 1.6 meters was allocated for the driver compartment. This should give plenty of room for legs, frame, and side windows.

Aerodynamic Needs

The design goal is low drag. Even though the speeds of these races will seldom exceed 55 miles per hour, low aerodynamic drag is of importance. In the 1990 Sunrayce, one square inch of drag area was estimated to be equivalent to six minutes of additional finishing time.[2] Since we cannot assume that mother nature will give us ideal racing conditions, the subject of low drag in crosswinds must also be addressed. The need for high efficiency means that the mechanical engineers will do their best to design a very low-weight car. This low weight offers yet another problem: a large car with low weight will be very susceptible to instability in cross winds, or when meeting other cars. This leads us to the second design goal, stability under normal operating conditions and with cross winds.

Design Implications of Low Drag

With the previous discussion, numeric goals can be set. The car must first be low drag, 0.13 or less(referenced to the projected frontal area). This is fairly typical for cars of this type.[3] The total aerodynamic drag can be broken down into different contributions.

1. skin friction drag,D_f
2. pressure drag,D_p
3. induced drag,D_i
4. parasitic drag,D_o

Skin friction drag is related to the wetted surface area and the type of flow over the body. The skin friction drag is dependent upon the type of boundary layer. A laminar boundary layer has lower skin friction drag than does a turbulent one. The total surface area cannot be significantly changed because the solar array requires such large surface areas to collect sunlight. The type of flow over the body can be controlled to some extent.

Pressure drag is created when the boundary layer actually separates from the surface of the body. The velocity of the airflow at the surface is always zero. Under normal conditions that velocity immediately begins to increase. When there is an adverse pressure gradient the airflow further from the surface slows. Flow separation occurs when the flow just off of the surface is stagnant,$(dv/dy)=0$.(figure1)

Induced drag is also called drag due to lift. It is the result of a high pressure underneath the body and a low pressure above the body. Air will flow around the side edges, wingtips in the case of aircraft, in an attempt to equalize the pressure. By keeping the lift near zero, induced drag can be essentially eliminated.

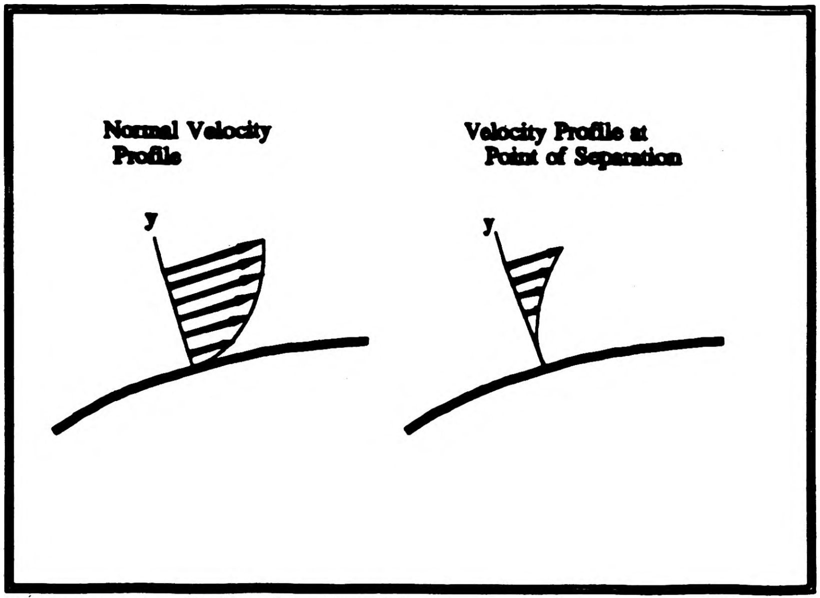


Figure 1. Velocity Profiles

The car needs a low drag characteristic even in a cross wind,otherwise a few windy days could leave us hours behind the competition. A side wind can be simplified by considering it as a change in the effective direction of the freestream flow.(figure 2)

An analysis of the effect of side winds can be performed if the body is sectioned in planes parallel to the wind.(figure 3) A component of the drag on these profiles contributes to the drag of the entire body and the other component pushes the car sideways.(figure 2) If this cross sections shape is a good aerodynamic shape, the drag and side forces will be low under crosswind conditions.

The parasitic drag is the drag due to seams, imperfections, mirrors, antennae, or anything else that extends from the body. This contribution to the drag can only be found through experimentation. This is beyond the scope of this project and, therefore, will not be referred to. Although, it should be understood that parasitic

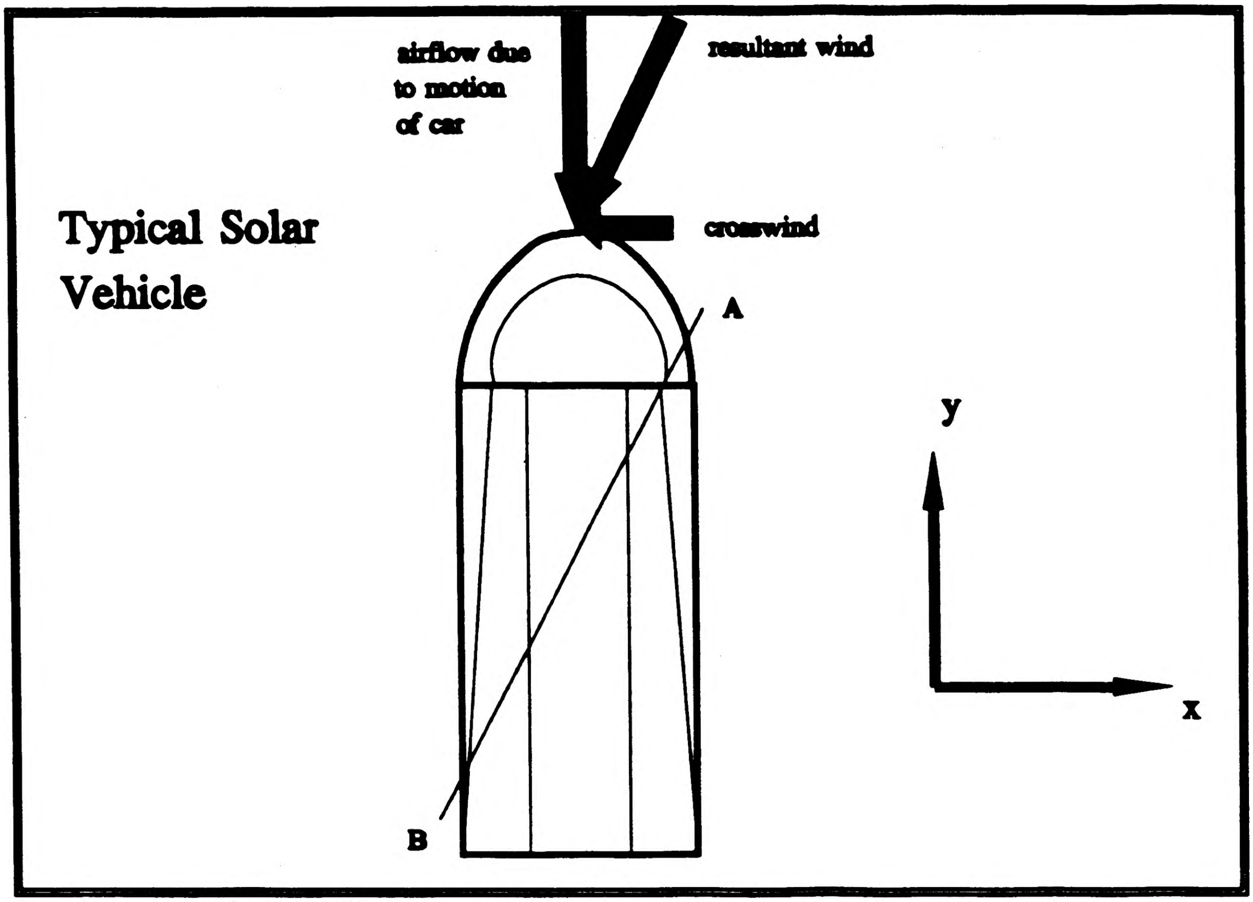


Figure 2. Relative Wind

drag could be a significant component of the drag. This does not inhibit our ability to design a good shape because it is simply a component of the drag to be summed for the total drag. It has no impact on the basic shape.

Design Implications of Good Stability

The car must be stable in cross winds, a low drag vehicle would be no good if it couldn't be kept on the road. This is a problem that has plagued solar race vehicles in the past.[3] To assure this, the vehicle should have little lift, a center of pressure with respect to the side below and behind the center of gravity, and to have a low side force under these wind conditions.
Again we have the idealization of cross winds changing the effective direction of the wind.(figure 2) The component in the negative x direction pushes the car sideways.

Also, the magnitude of the side force can be minimized by reducing the effective area when viewed from the side. This is because the magnitude of the aerodynamic force is related to effective cross sectional area.

A cars stability comes from its ability to grip the road. If the lift of the car is kept near zero, the tires will have more load on them and grip the road better. Thus, by lowering lift we can help the car mechanically overcome the aerodynamic side forces.

Additional Needs of Solar Power

The nature of the power of the vehicle offeres further design criteria. The bulk of the surface of the vehicle must be covered with flat solar cells approximately 4" square. To eliminate inefficiencies in the solar cell array, it is necessary to keep the areas where the solar cells are mounted as planar as possible. Also, solar power necessitates large surface areas. A high surface area means a high skin friction drag.

Solar power adds one further parameter to the design. As the solar cells heat up they become significantly less efficient. To cool the cells the boundary layer near the cells should be at a high velocity quickly to dissipate the heat. This is characteristic of a tubulent boundary layer.

Design Implications of Solar Power

The large planar areas on the car to facilitate mounting of the solar cells will encourage vortices and increase the chances of separation of the flow, especially in cross winds.

Turbulent flow over the solar cells will cool them and make them run more

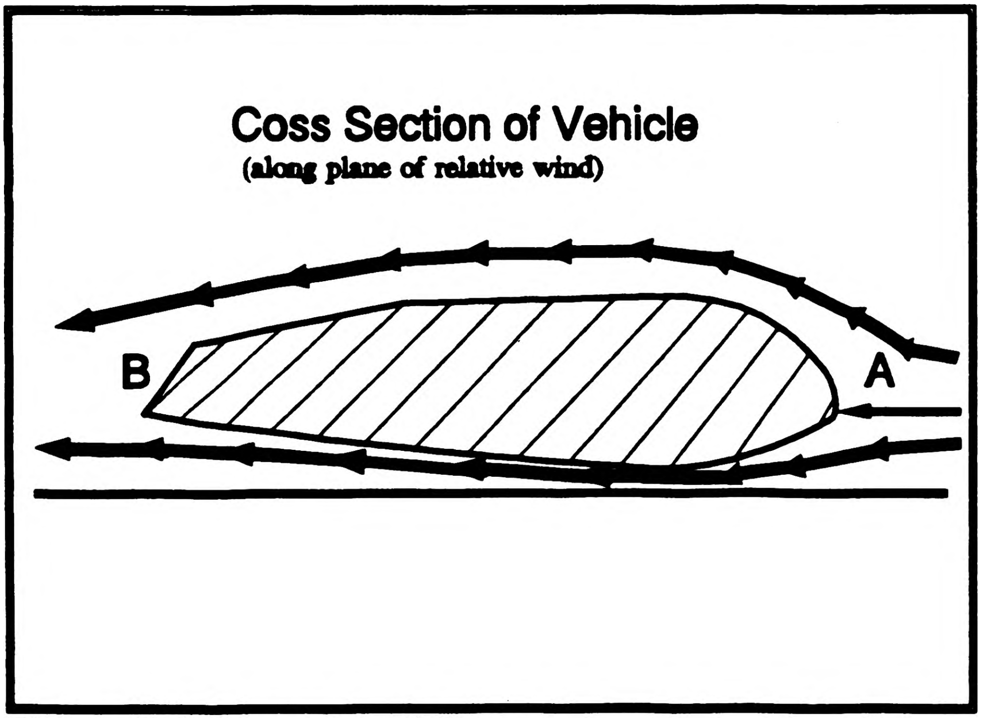


Figure 3. Cross-section of Car

efficiently. This, however, has a penalty. Turbulent flow has higher skin friction drag than does laminar flow. If the flow is laminar over the array, it may be best to trip the flow from laminar to turbulent. This will cause a drag penalty, but will increase the efficiency of the solar cells.[2]

ASSEMBLING BASIC SHAPE

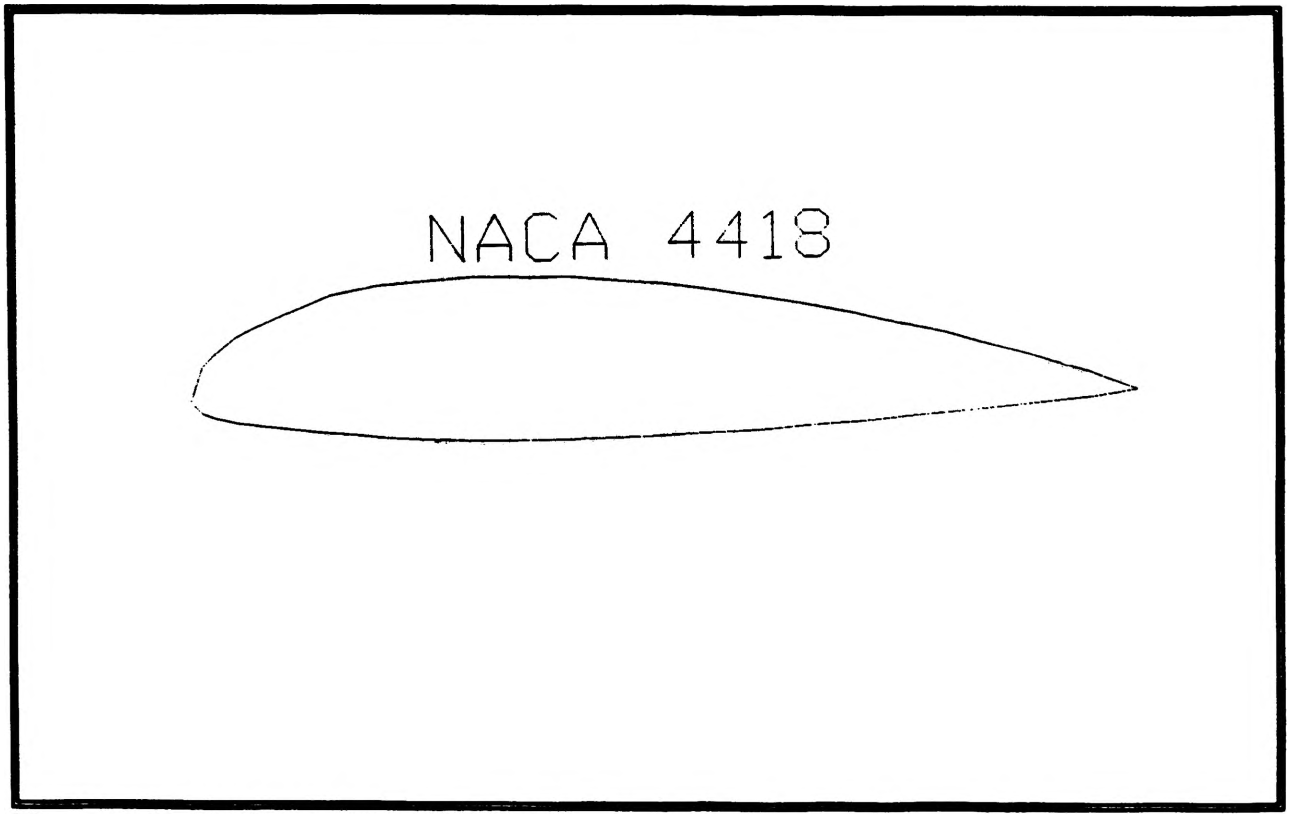


Figure 4. NACA 4418 Airfoil

The overall dimensions and placement of driver and array can be set from the influences of the race regulations. But, there is still no hint of what shape the car actually has. The beginning point is to define a general shape with the low drag and low side force characteristics we are interested in and then modify this ideal shape to fit the particular needs of the car. The car needs to be a shape that will achieve some degree of laminar flow and that minimizes separation. The logical choice for the side view of the car is a standard airfoil. An airfoil is designed to have little drag as well as produce lift. Ideally, we can utilize the low drag and destroy any unwanted lift. Using the overall dimensions set previously, the airfoil needs a thickness to chord ratio of 17, and a maximum thickness to be at a position 27% of the chord aft of the leading edge. This places the maximum height at the front of the solar array. Standard NACA airfoils have thickness to chord percentages of 16 and 18. The thicker airfoils are more desirable because they leave room to modify the shape of the car without brushing on the 1 meter minimum height rule. The NACA 4418 airfoil best fits these requirements. This airfoil has the desired thickness to chord percentage and a maximum thickness at about 27% of the chord. (drawing) Now consider the top view. It makes sense to make this view an airfoil shape as well. Unfortunately, there are no standard airfoils thick enough to fit the previously set width. The solution is to lay the top surface of an airfoil on each side of the car. A 4424 airfoil has the correct overall thickness and a position of maximum thickness near to that of the NACA 4418 airfoil.

Now, the only characteristic of the basic shape to address is the car's appearance from the front. To minimize separation and vortices in cross winds, the front view should not have any sharp corners. This leaves what is essentially a teardrop shape. "The body of frontal area S, which opposes a minimum drag to the airflow, is the well-known "drop-shaped" body..."[4]

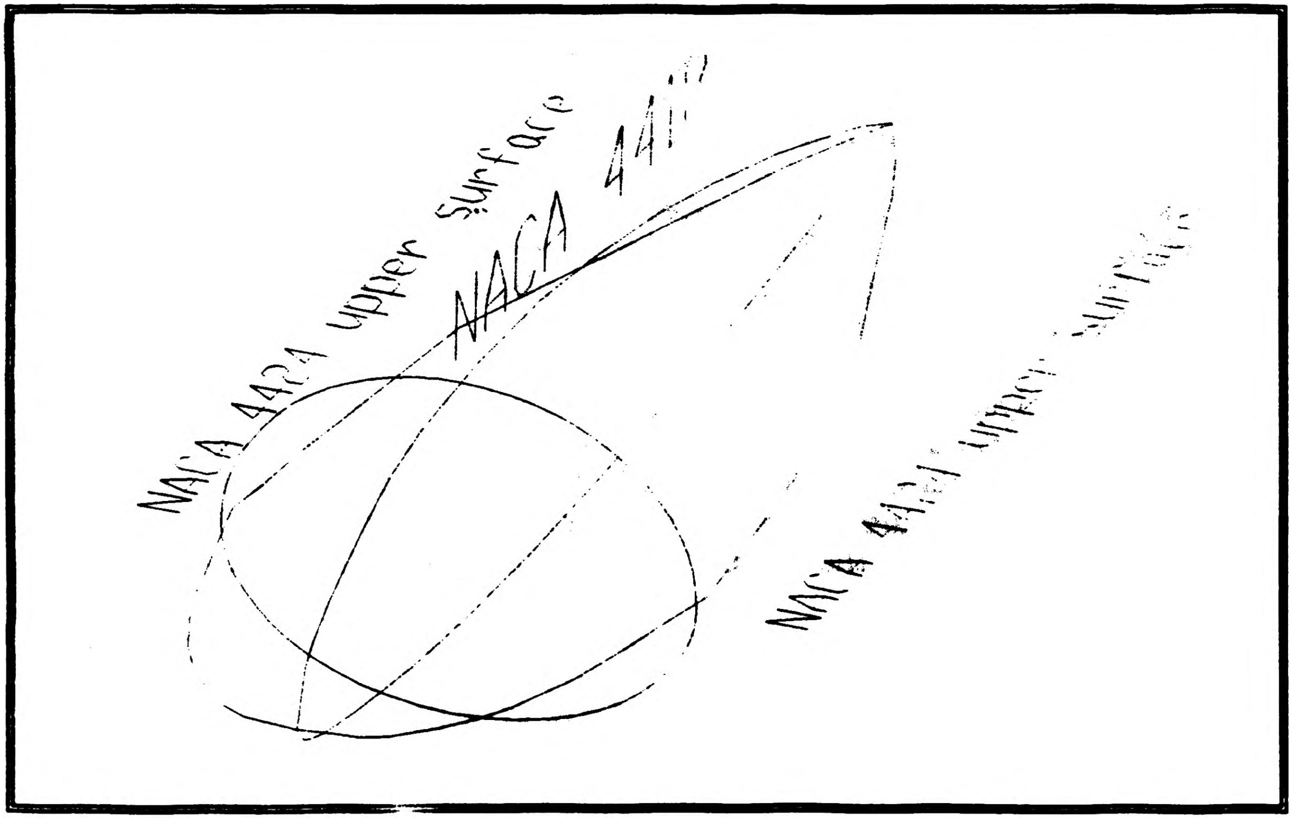


Figure 5. Basic Shape

MAKING BASIC SHAPE PRACTICAL

The teardrop shape now needs to be modified for practicality. The tapered tail of the teardrop shape can be widened out to provide room for mounting the solar cells. Secondly, the curved surface of the back of the car would be very difficult to mount solar cells on. Also, curved arrays have certain power losses associated with the way the power is managed after it leaves the cells. For these reasons the back of the car will be fit with plates that nearly fit the ideal shape, and have the maximum "useable" surface area. Because the cells are square, some surface area will be wasted.(drawing)

ANALYSIS OF DESIGN

An analysis of the basic shape just constructed points out some areas of interest. An approximate drag figure can be obtained by assuming the car is a wing with the NACA 4418 airfoil, and having the same projected frontal area. Using the equation:

$$D=\frac{1}{2}\rho\,(V_{\infty}^{2})\,SC_{d} \tag{1}$$

where ρ is the freestream density, V is freestream velocity, S is the projected frontal area, and C_d is the profile coefficient of drag. A total drag estimate of 5.03 N is obatined at 55 mph and at sea level standard conditions. The shape is low drag but this shape should also produce some lift.

A flaw in out analysis is that all of the analytic construction of the model ignored one important factor. This car will not be travelling through freestream airflow without any effects from other bodies. This car will be moving very close to the ground which has a boundary layer of its own. A computational fluid dynamics program,CFD, could model the ground plane. From that data the shape can be modified accordingly.

READYING DRAWINGS FOR CFD

Electronic Data Systems agreed to allow all of the teams entered in the Sunrayce to utilize their computational fluid dynamics services. The cad drawings had to be readied for their process. The shape of the car had to be converted from a highly curved surface to a series of flat panels. This is because the program calculates the pressure on the surface of the car for a series of plates. As you use a more curved surface, the number of plates goes up and it takes longer and longer for the program to run.

Electronic Data Systems uses the program VS-AERO. With this package EDS modeled the ground plane along with the car. The effects of the ground plane will depend upon how high above the ground the car is. Reflecting on previous vehicles and advice from the solar car team, the ground clearance was set at six inches for the lowest point on the bottom of the car.

CFD RESULTS

This first test was done at 55 mph and no crosswind. VS-AERO outputs numerical results as well as graphic representations of the flow around the car. The numerical results are summarized as follows:

$C_d = 0.001238$ $C_l = -.0230$ $C_m = -0.012$
all referenced to the wetted area- 26 m^2

These figures are within an order of magnitude. Using equation 1, this gives us a total drag of 1.19 Newtons, compared to our original estimate of 5.03 Newtons. These figures are fairly close considering that the computational fluid dynamics figure is within an order of magnitude and the original estimate was a crude estimation of the shape. The total lift is figured using equation 2.

$$L=\frac{1}{2}\rho V_\infty^2 S C_l \qquad (2)$$

where ρ is the freestream density, V is freestream velocity, S is the total wetted area, and C_l is the coefficient of lift
This gives a lift of -222 Newtons at 55 miles per hour and standard sea level conditions.

The total moment can be found using equation 3.

$$M=\frac{1}{2}\rho V_\infty^2 S C_m l \qquad (3)$$

where ρ is the freestream density, V is freestream velocity, S is the total wetted area, C_m is the moment coefficient, and l is the length of the car.
The moment is -780 Newton meters about the one fourth the length of the car aft of the front at 55 miles per hour and standard sea level conditions.

These figures indicate that we have constructed a low drag shape with little lift and small moments. The most valuable information came from the graphic drawings. The drawing showing streamlines showed that with no crosswind there was little or no separation.

The skin friction photo showed a notable increase in the skin friction drag at about 1.45 meters from the front of the car. This is an area of likely transition of laminar to turbulent flow. This is upstream from the solar array, so the cells should have good cooling.

The photos also showed some problems. There was a large increase in pressure underneath the car at the lowest point. This high pressure area under the car means greater lift and drag. The photos of the skin friction drag showed areas of disturbed flow behind the wheels.

REDSIGN ON THE BASIS OF CFD

To avoid the high pressure area underneath the bottom of the car the bottom of the car was flattened. Ideally, this will give the airflow a larger area to flow through and reduce the pressure. If the bottom point on the car is raised two inches the new ground clearance. The two inch figure was reached arbitrarily, there is no way to know how much to raise the bottom. The figure simply must be set and tried.

To solve the problem with the disturbances around the wheels, wheel pants were fitted to the car. The pants had the shape of an airfoil.

CFD RESULTS FROM SECOND ANALYSIS

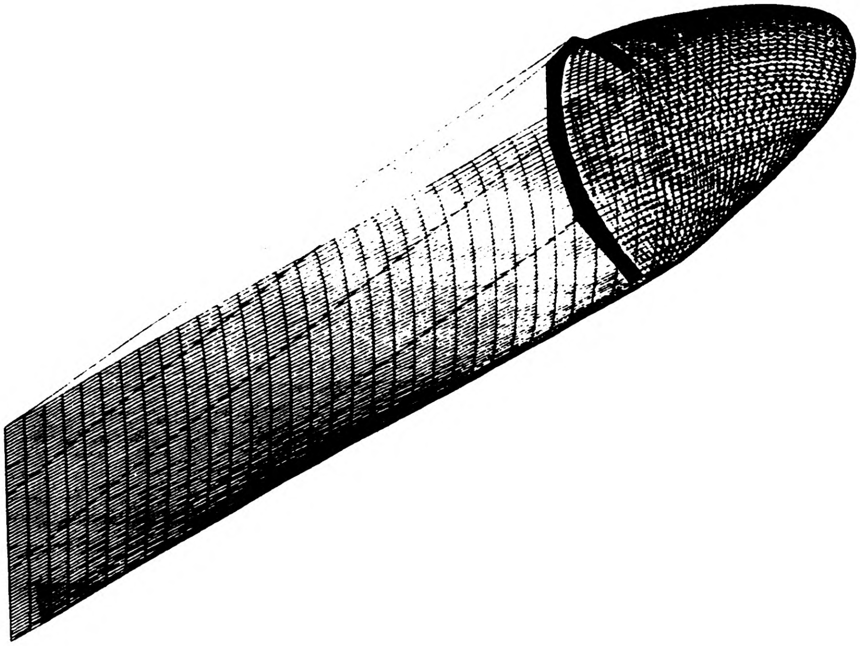
Numerically, the results from the second test were almost the same as the first. The figures are as follows:

$C_d = 0.00012$ $C_l = -0.02478$ $C_m = -0.0146$

all referenced to the new wetted area of 24.6 m^2

The drag and lift were slightly less.

CONCLUSIONS ABOUT SHAPE



The final design is a shape that has low drag and good stablity. The flow is kept laminar for the first 1.45 meters. The exact coefficient of drag is not known, but it is near 0.00012 referenced to the total wetted area. The biggest problem with the flow over the car was fixed and resulted in a very small decrease in the drag. Cross sections parallel to the relative wind are fairly aerodynamics shapes so there should be few problems with crosswinds. The car has low lift and low moments indicating a fairly stable car.

SUGGESTIONS FOR FURTHER RESEARCH

The dynamic stability of a vehicle in a side wind is dependent upon the location of the center of pressure with respect to the center of gravity. This center of pressure can be found experimentally in the wind tunnel.

The flow over the surface of the car might be improved if some flow visualization methods were used on a wind tunnel model. This would show problem areas and confirm the computational fluid dynamics already performed.

A wind tunnel model has been constructed. This was done by sectioning the car with a series of vertical planes, starting from the front and moving back. The distance

between the planes should be equal to the thickness of the wood sheets to be used in the model. Plot the cross sections. Cut out plywood cross sections. Assemble the plywood crossections . This gives a jagged edged shape of the car. Sand off corners keeping in mind that the curve on one edge of the plywood is exactly the right shape.

ACKNOWLEDGEMENTS

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