Aerodynamic

Analysis and Fabrication of Formula Style Race Car Chassis

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Abstract

The purpose of this project is to design and fabricate a full aerodynamic package for WPI’s Formula SAE team while adhering to the rules set forth by Society of Automotive Engineers International. The front and rear multi-element wings along with the underbody diffuser were designed to generate a maximum low-speed down-force while maintaining minimum drag. The complementing body design utilizes aerodynamic loading for quality race performance by reducing wake vortex generation. Three different types of analysis were used in the completion of this project: wind tunnel testing, computational fluid dynamics, and track testing.
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Goal statement
At the beginning of the project a set of achievable goals were set:

- Decide upon an airfoil
- Modify airfoil to meet rule restrictions
- Design the front and rear wing that will increase the performance of WPI’s FSAE racecar
- Design a body cover that will reduce drag and work with underbody diffuser
- Design an effective underbody diffuser
- Design side pods that will utilize aerodynamic design and effectively cool the radiators
- Decide on material for fabrication
- Fabricate aerodynamic package models for future team use
- Fabricate each element in a timely manner
- Enter in the “Best Body competition” at competition in May
1. Introduction

The design and fabricate of a Formula SAE car for student competition has been a tradition for almost 20 years. The goal of this project is to design and fabricate an aerodynamic package for the WPI FSAE car to increase to performance. The addition of an aerodynamic package to a formula style race car heightens the efficiency of the cars performance. Each component of the aerodynamic package, the wings, diffuser, nose cone, and side pods, contribute to the overall down-force and the reduction of drag. Down-force or negative life creates a downward force that increases the traction of the car, which is especially beneficial during turns. This will be beneficial during the endurance trail during the competition. The endurance trial consists of a track with numerous turns. While the increase of overall down-force is desirable, the team also takes in to account the drag, force of the air on the car. The addition of the body will reduce the overall drag. Also the front wing will assist in reducing the drag caused by the front tires. The final product will increase the overall performance WPI’s FSAE car for competition in May.

1.1. Purpose of Aerodynamics in racecars

In today's world of racing the aerodynamic engineers have two primary focuses. The first: creation of downforce in order to improve the cars handing in the corners and second, to minimize the drag that acts to slow the car down. This leads to the fundamental question in any modern racing team: how to create maximum amount of downforce for the minimal amount of drag? Trying to answer this question engineers need to study every single surface of a modern formula race car, from the shape of the suspension to that of the driver’s helmet.

The principles which allow aircraft to fly are also valid for race cars. The only difference being the wing is mounted upside down producing downforce instead of lift. The wing of a race car is shaped so that the air moving over the top of the wing moves slower than the air beneath it. Since the air pressure under the wing is lower than that above the wing, downforce is produced.
The shape of the chassis is also similar to the upside down airfoil discussed earlier. The shape of the underbody creates an area of low pressure between the bottom of the car and the racing surface. This sucks the car to road resulting in better corner handling. Wings are also used in the front and rear of the car in an effort to generate more downforce.

1.2. History of aerodynamic in motorsport

It all started with the revolutionary Can-Am Chaparral, Figure 2. The 2E model established the norm for virtually all race cars built since. With its radiators moved into two ducted pods on either side of the cockpit and a large wing mounted several feet above the rear of the car, it reflected the newest trends in aerodynamic. The wing was attached directly to the rear hubs, loading the tires, for extra adhesion while cornering. A ducted nose channeled air from the front of the car up, creating extra down force and pinning the cars to the track for greater traction and increased cornering speed.
The next big step in the history of aerodynamics came in 1972. Colin Chapman, the designer and founder of Lotus, introduced the Lotus 72. For better air penetration and higher speeds it had a pointed 'shovel' nose and a nose-cone in the form of a wedge. In 1978 Team Lotus introduced the 'ground effect' phenomenon. By shaping of the underside of the car the Lotus designers managed to effectively generated a vacuum between the road and the car moving at speed.
Nowadays modern racecars show off an extreme aerodynamic package with almost as much in common with a jet fighter as with an ordinary road car. Aerodynamics has become integral part on the road to success in the sport with teams spending millions of dollars on research and development in the field each year.

Figure 4: Typical design of a modern day formula race car
2. Background research

2.1. FSAE rules

The overall goal of this project is to design and fabricate a full aerodynamic package for the WPI's Formula SAE team while adhering to the rules set forth by the Society of Automotive Engineers International. Each year these rules are updated based on past performances of the teams in an effort to maintain fair and safe competition while giving teams design flexibility and freedom to express creativity through engineering design. While the rules cover the design and fabrication of the entire car as well as the judging categories for the car, this section will only review the parts that are relevant to this project, the aerodynamic package.

The rules that apply to this project are under section 3.7.1 Aero Dynamics and Ground Effects. This section reviews the requirements that all the aerodynamic devices must follow. The section reads as follows:

3.7.1 Aero Dynamics and Ground Effects

All aerodynamic devices must satisfy the following requirements:

3.7.1.1 Location

In plan view, no part of any aerodynamic device, wing, undertray or splitter can be further forward than 460 mm (18 inches) forward of the fronts of the front tires, and no further rearward than the rear of the rear tires. No part of any such device can be wider than the outside of the front tires measured at the height of the front hubs.

3.7.1.2 Driver Egress Requirements

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1 2008 Formula SAE® Rules
Egress from the vehicle within the time set in section 3.4.7 “Driver Egress,” must not require any movement of the wing or wings or their mountings. The wing or wings must be mounted in such positions, and sturdily enough, that any accident is unlikely to deform the wings or their mountings in such a way to block the driver’s egress.

3.7.1.3 Wing Edges - Minimum Radii

All wing leading edges must have a minimum radius 12.7 mm (0.5 inch). Wing leading edges must be as blunt or blunter than the required radii for an arc of plus or minus 45 degrees (± 45°) centered on a plane parallel to the ground or similar reference plane for all incidence angles which lie within the range of adjustment of the wing or wing element. If leading edge slats or slots are used, both the fronts of the slats or slots and of the main body of the wings must meet the minimum radius rules.

3.7.1.4 Other Edge Radii Limitations

All wing edges, end plates, Gurney flaps, wicker bills, splitters undertrays and any other wing accessories must have minimum edge radii of at least 3 mm (1/8 inch) i.e., this means at least a 6 mm (1/4 inch) thick edge.

3.7.1.5 Wing Edge Restrictions

No small radius edges may be included anywhere on the wings in such a way that would violate the intent of these rules (e.g. vortex generators with thin edges, sharp square corners on end plates, etc.).

3.7.1.6 Ground Effect Devices – Prohibited

No power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling. Power ground effects are prohibited.
The main point behind these rules is to keep the participants safe while still allowing for engineering creativeness. For example, the wings must be mounted as to have no affect on the driver’s egress from the car even in the event of a crash. This rule helps keep the driver safe from the unlikely event of a crash. The rules also include other safety regulations, such as minimum wing edge radii along with trailing edge thickness. The leading wing edge radii must be at least 0.5 inches and a trailing edge thickness of ¼ inches. While these rules affect the performance by a fraction, it allows the participants to use actual engineering problem solving skills. Real world engineering, whether it is automotive design, architecture, or power plant management, all follow rules and regulations, and this competition helps prepare it’s participants in dealing with restrictions.

2.2. Old MQP’s

One of our most important resources is the “Formula SAE Aerodynamic System Design” Major Qualifying Project carried out by Christopher Cammack and David Lenhardt. Their project was aimed at improving the on-track performance of the 2002 Formula SAE racecar using an aerodynamic system. They used a multiple wing arrangement combined with an underbody diffuser to generate maximum low speed downforce within vehicle constraints and FSAE rules. The airfoils selection had been made based on lift to drag ratio and maximum lift characteristics. This led them to selecting the Sleigh 1223 airfoil. After modification of the airfoil profile in order to comply with the FSAE rules for minimum wing edge radii, the aerodynamic system was predicted to generate approximately 20 pounds of downforce and less than one pound of drag at 16mph. One of the main limiting factors came from rule 3.7.11, which states that the width of the wing cannot exceed the overall width of the car. The increase of lift may be greater than 50% when the ground clearance is less than half of the airfoil cord.
2.3. Similar Applications

The use of aerodynamics in the design process of modern racing cars is as obvious to see as in the world of aviation. And, in fact, the inspiration for many of the most revolutionary advances in race car aerodynamics came directly from aircraft. Those that were on the cutting edge of this new technology (though they may or may not take home the win), had an advantage that was undeniable, and it did not take long for the importance of aerodynamics to be recognized by the entire racing community. Though to date, Formula 1 leads all other motorsport in the field of aerodynamics, there are few genres of racing that do not benefit from the technology researched in their ongoing battle to cross the finish line first.

Since the sport began, there has always been steady support from the vehicle manufacturers whose badge these cars often wear. Granted that it is often overshadowed by the large and very colorful logos of the teams other sponsors, but it is always there. And it isn’t just the racing teams that benefit from this. The new and innovative ideas that roll out of the research and development departments of racing teams continue to benefit the commercial car industry as well. As fuel prices continue to climb as they have been doing for some time now, the demand is growing for vehicles that are more and more fuel efficient, and an integral part of achieving this is the application of aerodynamic technology that we saw applied first in racing.

As a simple example of the difference this technology has made on the automotive industry, please examine the following image of GM’s 1964 Impala:
When this car was still rolling off of the assembly line, the average price for a gallon of gas in the U.S. was 30 cents. The average family was not very concerned with how much they were paying for fuel. However, in this day and age, people are commuting farther for their jobs every day, and indeed are traveling farther for many things as part of their usual routine. With fuel costing more than 600% of what it used to, driving a vehicle that averages 15 miles per gallon is no longer acceptable. In addition to all of the mechanical changes and refinements that have been made since then, the effort to improve aerodynamic efficiency are obvious to see. The following image is of GM’s 2006 Impala:

The difference speaks for itself. The long, backswept windshield, and the spoiler on the rear deck lid are just a couple of the obvious changes made with aerodynamics in mind. Other practices commonly used in commercial car design include the use of front air dams to direct airflow around
the car rather than letting it flow underneath, and increasing the “rake”. That is to say that the car is set up to be lower in the front than it is in the rear, which creates a simple venture effect allowing the air to flow more easily under the car.
3. Design Methodology

3.1. Configuration of Aerodynamic Package

The choice the team had to make was the overall make up of the aerodynamic package for WPI's FSAE racecar, was the elements to include. For this project, the team wanted to include a front wing, rear wing, side pods, a diffuser, a nose cone, and the body shell. Figure 7 shows the layout of the aerodynamic package on the car.

![Solidworks Model of the Design concept of the car](image)

**Figure 7: Solidworks Model of the Design concept of the car**

The front wing is located in the front of the tires low to the ground. This creates a down force at the front of the car. This placement also helps force flow over the tires. The rear wing is located behind the main roll hoop, above the rear tires. Because there is a rear body, the rear wing can be placed closer to the tires. The body is designed to reduce drag across the car. The rear body actually helps reduce the turbulent flow to the rear wing, thus increasing the efficiency of the rear wing. The side pods assist in reducing the drag across the car as well as channeling flow to cool the radiators and protect them. Lastly, the underbody diffuser, generates the most down force for the car and
places that force under the driver, balancing out the forces from the front and rear wing. The reason it creates the most down force is because it turns the whole car into an airfoil itself.

While each of the components making up the aerodynamic package for the racecar is improving the efficiency of the car separately, they actually work together for the best result. For example, without the rear body, the rear wing would not need to be placed higher and would be less effective. Without the body, the diffuser would be less efficient because the flow over the top of the car would be less ideal for the best results. All the components work together to increase the overall efficiency and performance of the WPI FSAE racecar.

### 3.2. Material Selection

In designing a racecar for a formula SAE racecar, the aerodynamic package was fabricated from carbon fiber. When deciding the material for fabrication, the material decided was a composite material. A composite material is a material made up of two or more materials. In this case, carbon fiber is made up of fiber that is made up of carbon fibers and a resin, epoxy. The other material that the team looked at for an option for fabrication was Aramid or Kevlar. Aramid is a synthetic material that is made up of polymer strings, where carbon fiber is made up of mostly carbon atoms.

Because one of the goals of this project was to increase downforce while limiting the amount of weight added to the overall weight if the car, the team needed a lightweight material to construct the each element of the aerodynamic package. The team needed for a tough but lightweight material. The material needed to be light in weight, but it also needed to withstand the forces that have been calculated that the aerodynamic package would take. The other factors that went in to the decision of the material for the body were the cost, type of weave, and manufacturability. The team decided to construct a design matrix to determine the best material for this project. Figure 8 shows the design matrix.
For the design matrix, each category was given a rating on a scale of 1 to 10, 10 being the best and 1 being not so good. Then each property was weighted to give an overall final score of the material. The properties that were rated were cost, manufacturability, overall strength, weight, and weave.

Cost was based on price per square foot; of course this was an important factor for the team because of budget issues. Weight was another important factor because the team wanted to gain the most out of the material while not contributing to the overall weight of the car. The other important factor was the weave. Weave in this case was either satin (for the aramid, Kevlar) or twill (for the carbon fiber). Weave describes how the fibers are woven together. The reason why this property was important in the decision process is because depending how the material is woven affects its overall strength as well as affecting the drag. As reducing the drag was one of this projects goals. The twill in this case causes the least amount of drag because of the way it’s woven. Figure 9 shows an example of a weave of each material.

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The less important characteristics but still were valuable enough for deciding upon the best material, were manufacturability and overall strength. The manufacturability did not add much weight to the design matrix because the team’s background in using composite materials was low so it would be a good learning experience and the difficulty on manufacturability would not have effect on the team. The overall strength was weighted as middle ground for importance because while the material needed was not going to be used for load bearing forces, they would still need to be fairly strong for the forces from the air on the different elements of the aerodynamic package.

Once all the information was imputed in to the design matrix, the best choice for this project turned out to be carbon fiber.

### 3.3. Airfoils Selection and modification

Based on previous years design choices as well as on the extensive airfoil data on UIUC’s webpage we decided to use the S1223 airfoil. This airfoil was selected because of its superb lifting capabilities at low Reynolds numbers. Based on foil data and wind tunnel test form previous WPI’s FSAE team as well as form heavy lift cargo competitions, the maximum coefficients of lift and drag are 2.1 and .005 respectively. A cross section view of the S1223 airfoil is presented below as Figure 10:
Even though such suitable airfoil was found we still needed to comply with FSAE’s rules concerning the minimum radii requirement and its bluntness. This lead us do having to modify the existing S1223 airfoil and collect our own data concerning the lift to drag ratios as well as the pitching moment characteristics. The final result was the custom made airfoil presented below:
3.4. Front Wing

Usually the front wing of a formula car is suspended from the nose and spans the whole width of the car. Onto this are fitted one or more flaps which make up the adjustable parts of the wing. On each end of the main one can find endplates. These are used to make sure that there is no leakage of pressure thus maintaining airflow above and beneath the wing rather than around it. The endplates also play a crucial role in influencing the airflow around the front tires.

![Front Wing Configuration](Image)

Figure 12: Sample of a front wing configuration

Since the front wing is such a simple shape, the flow around it can be considered a classical flow around an inverted airfoil. In this case the first element provides air flow to the second element lower surface. The second element chord is usually reduced at the centre of the span to decrease the deflected flow downstream and to avoid interaction between the nose and the second element. The endplates main aim is to deflect the flow from the front wheels. The latter influence the air flow in a way that the air close to the tire surfaces may be a reverse flow compared to the overall flow coming from upstream.

Another very important consideration is the ground clearance of the front wing. Since it usually located between 2.75 and 3.94 in the ground effect it experiences is really strong. Due to the fact that the rest of the car operates in the wake generated by the wing it is important to tune the wake profile of the wing. The lower to the ground, the better the sealing of the front wing endplates and the more efficient the front wing. The final design of the rear wing is shown in Figure 13.
3.5 Rear Wing

The rear wing is one of the key elements in creating downforce for competition cars. The goal of the rear wing is to create the most negative life, downforce, while reducing the amount of drag caused by the wing. Even though the wing creates drag, depending on the design of the selected airfoil, the downforce can be much greater than the drag, also known as the negative lift (downforce) coefficient. The airfoil that is selected and modified for this project is discussed in the airfoil section. The other elements in design of the rear wing are the endplates, number of wing elements, and the mounting of the wing.

Adding endplates to the either wing reduces tip losses. Because the upper and lower surfaces of the wing have different pressures, the higher pressure on the top of the wing will migrate to the lower pressure underneath the wing. This causes the loss of downforce because of the air is moving to the lower pressure thus deceasing the higher pressure. Choosing the appropriate size of the endplates greatly affects the flow of the air over the wing; it assists in channeling the air over the wing and reduces the turbulent flow. The addition of endplates also reduces the turbulent flow from the rear tires, keeping the flow closer to laminar flow over the wing.

Because downforce = ½ *ρACLv², by increasing the area, A, of the wing by adding additional wing elements known as flaps the downforce increases. For most cars, the flaps are a scaled down
version of the airfoil. For this project, the flaps are a scaled down version of the airfoil selected that had to be slightly modified again because of the FSAE rules.

By adding additional elements to the rear wing is more beneficial instead of one airfoil. The reason behind that are several reasons. First, the effective camber increases because the multi-element wing can be considered one wing. Camber is the curvature of the wing. It is a asymmetric between the top and bottom curvature of the airfoil. Figure 14 shows the camber line in the modified airfoil that was selected for the wing.

![Figure 14: Camber line shown in modified airfoil](image1)

As seen in Figure 15, the camber line in the final wing arrangement is more curved. This allows for the greater down force, while reducing the drag.

![Figure 15: Camber line of final wing arrangement](image2)
The gaps that the flaps create do not take away from the pressure differences. It actually helps in maintaining a greater down force. For most multi-element wing cars, the flaps create a narrow gap. This gap is generally 1-2% of the cord and overlaps 1-4% of the cord. The most important factor of the gap is that it has a convergence of small to large. This creates a nozzle effect. This accelerates the air through the gaps entering at a lower pressure and increased energy. The analysis of this will be looked at in a further section.

In the first iteration of the rear wing, seen in Figure 16, the endplates extend down to the rear body and attach to the body. The original idea behind using the endplates as the mounting point was to reduce any interference that will affect the flow under the wing. Most cars with a rear wing mount from the middle of the rear to the car. While this is an easier for construction, it disrupts flow under the wing. The other benefit to this design is the turbulent flow over the rear tires do not disturb the flow under the rear wing.

The final configuration of the rear wing is seen below, in Figure 17. It was further discovered for the timeline of the project that the difficulty behind fabricating the first design would prove to be very difficult. While the design was a more efficient and idea wing design, the difficulty behind the fabrication was not feasible for this project. The final design for the wing was to reduce the endplates and create a mounting point in the center of the first wing element with either steel or aluminum rods to keep the drag to a minimum and the flow undisturbed as possible.
3.6 Side Pods

The number one goal of the side pods is to protect the radiators from any damage. The side pods are basically part of the body, but are designed to channel flow to the radiators and over the rear tires. In the design for the side pods in this project, the team wanted to add in another element, to create a nozzle as part of the side pod. Below in Figure 18 is shown the design of the left side pod. The exterior body of the side pod is designed to reduce the drag over the car making the car more efficient.
The channel within the side pod is designed to accelerated flow over the radiators cooling the engine. As the air is accelerated through the side pod, it creates a pressure difference and helps to reduce more drag. The other idea that was introduced with the design of the side pod was to use the underbody diffuser to diffuse some airflow under the car out and over the rear tires. Designing the side pods to have the airflow over the rear tires greatly reduces the drag. Because the tires spin opposite the flow, they create an abundance of turbulent flow. This makes the car less efficient and effectively can slow the car down. Designing the air to flow around the tires will greatly reduce the amount of force from drag. The basic design behind the side pods are simple, to protect the radiators. This project looked into design the most efficient and beneficial side pods for the car.

3.7. Full Body Cover

Looking into the way the body shape affects pressure distribution along the centerline of the car is probably one of the most important considerations when designing a car body. As presented in the figure below there is a stagnation point at the front most part of the body.

![Figure 19: Pressure Coefficient Distribution over a car shape](image)

The flow then accelerates over the hood and due to this the pressure drops and becomes negative. At the root of the windshield the flow slows down and the pressure increases. The flow
then reaccelerates over the roof of the vehicle where the pressure drops once again. At the rear of the vehicle the process is reversed and at its rear most point the flow separates due to its shape.

The pressure distribution on the car surface was used for identifying where cooling inlets and exits should be placed. Surface pressure distributions have an enormous influence on the flow over the car. The longer the flow stays attached and the boundary layer undisturbed, the free stream will stay laminar for a longer distance along the body surface resulting in less friction and therefore less drag. Therefore by knowing the local speed and the slope of the pressure distribution we can predict drag and boundary layer behavior using computational fluid dynamics.

The rear wing is the biggest problem when it comes to the airflow coming towards it, with it being broken up and disrupted by the wheels, rollover bars and all the other vehicle components preceding it. Keeping up with the latest trends in motorsports we used ‘narrow waist’ design, where the rear of the car is made as narrow and low as possible. This is done to reduce drag and maximizes the amount of air available to the rear wing. A raised nose was also used in order to increase the airflow under the flat under body and the front wing.

3.8. Underbody diffuser

With FSAE rules banning the use of a powered suction device for drawing air and the necessity of a 1 inch ground clearance, the way forward is to design profiled underbody channels in order to prevent sideways migration of air. There are 3 main factors to be considered when designing such a device: the ground clearance, the underside roughness and the shape of the underside. The development of a boundary layer under the car and keeping an attached flow are also of vital importance to the underbody airflow in an attempt to produce downforce. We have also considered the correlation between the airflow speed underneath the car and its proximity to the ground. By making the gap between the ground and the underbody minimal we can cause the air to accelerate, decreasing the static pressure, as if in a venturi tube. For this it is necessary first to channel the airflow into a narrowing section so that its velocity increases through the throat in accordance with the conservation of mass law. This is what actually generates the downforce. Next
we need to slow the flow back down to ambient in a gradual and controlled manner without causing any flow separation. Raising the rear section of the car allows us to obtain the necessary space for setting up the diffuser. Another important issue relating to diffusers is boundary layer development along the underside of the car. As the boundary layer thickens towards the rear the effective angle of the diffuser reduces. Since there isn't a set database for diffuser shape as there is for wings we used CFD to model different configurations in order to find an optimized shape.
4. Design Analysis (thought CFD)

4.1. Airfoil Analysis

If one wishes to follow the practices that pertain to being a good engineer, they must make the very important link between prediction through calculation, and physical tests. There exists no better way to bring a design from concept to reality, while ensuring the results that one desires. Interestingly enough, it was found to be rather difficult to find a lot of information concerning the best method for optimizing a multi-element wing, so starting at the beginning seemed the most viable option.

![Figure 20: Original Airfoil](image)

Figure 20: Original Airfoil

The vast majority of CFD that was done for this project was done in Cosmos FloWorks. The reason for this is that most of the car (including the mechanical side of design as well as the body design) was modeled in SolidWorks, and FloWorks is a very powerful visual tool on top of being a computational tool for internal and external flow. Using FloWorks, the optimization process was begun by testing the modified airfoil against the original in an effort to observe the change in the airfoils effectiveness. Having chosen the S1223 airfoil as seen below for its proven effectiveness in providing high lift at low speeds, we were starting with a very good platform. However, since the
rules of FSAE state that any leading edge of an airfoil used must have a minimum radius of .5 inches over a sweep of 90 degrees, the S1223 required modification. The final shape of the modified S1223 chosen is shown Figure 21.

![Modified airfoil for wing](image)

**Figure 21: Modified airfoil for wing**

Although simple enough to do, modifying an airfoil that has been specifically chosen because of its efficient lift producing shape has obvious ramifications. Without testing the new shape, there is no way of conclusively knowing if the airfoil still works, as it should. So, to make sure that we did not ruin the way our airfoil behaves in a stream of airflow, we began our testing in FloWorks pitting the modified airfoil shape against the unmodified shape. With aerodynamic efficiency being the area of primary interest for this first test, a simple comparison of lift to drag ratios will be a good indication that the modified airfoil is still providing good lift (down force as it will be applied to the final car) at low speed.

The following table shows some of the numerical results from these tests. All of the tests to follow were run at an air speed of 30 mph, as it is about the speed we expect to see while running the car on the skid pad at competition. Both airfoils were set at a chord length of 10”. Standard pressure (14.7psi) and a temperature of 68°F were also applied. The initial results are shown in Table 1.
In the interests of getting the most accurate numbers possible, the airfoils were plotted in SolidWorks, and extruded to be very wide, while the computational domain was kept narrow (as can be seen at the bottom of this page). This, in effect, nullifies any effect that vortices forming at the wing tips could have on these initial numbers. In later tests it will be important to take these vortices into account, as they will produce drag on the final wings, but they do not concern us at this early stage of development. The forces from these tests appear small as a result of the narrow computational domain.

From the table not only do we see that the modified shape of the airfoil still works well, but from looking at the lift to drag ratios, we can see that it is actually producing more lift with respect to how much drag it produces. Our modified shape is, in fact, more efficient at this angle of attack.

Shown to the right is a visualization of the airflow over the original S1223 airfoil in the form of streamlines.

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<th>$D$</th>
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Table 1: Initial results of CFD of Airfoil
Their change in color is representative of the change in pressure induced by the change in airspeed. Blue represents low pressure, and red represents high pressure. This will remain the convention for all visuals of flow through the rest of the CFD sections, and should be noted. With this in mind, you can see the high pressure forming at the leading edge of the airfoil near the stagnation point. You can also see the center of pressure forming near the quarter-chord point on the bottom of the airfoil.

This is an image of the modified profile from this test. It is clear from the streamlines that the blunter leading edge has affected the way this profile cuts the air. You can also see here that the
low pressure is much more evenly distributed over the lower surface of the airfoil. This being the case, it can be hypothesized that the wing will apply less of a moment to the body it is attached to, but this subject is more of a concern in aircraft design than it is here.

Notice the gap between the upper surface of the airfoil and the airflow. This is due to flow separation, which can drastically reduce the airfoils efficiency. Though we can already see that the airfoil has not been affected by the change in shape too adversely, the same test was run again. Using a steeper angle of attack in hopes to move the point of separation further back on the airfoil, we hoped to attain numerical data from a setup that is closer to the orientation that the final wing will be in. The following table shows the results of this new test:

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Table 2: Results at angle of 8

We can see from these results that both airfoils are producing a considerably larger amount of lift than they were in the first test.

Figure 24: screenshot of airfoil at 8 degrees

Not only that, but both are producing it almost twice as efficiently (with the modified airfoil remaining still the most efficient) as they did in the first test. In looking at the images from this test,
it is plain to see why. Although it is a bit more difficult to pinpoint where the point of separation is on the airfoil, it is clear that it is much further back on the airfoil. Also, in comparison to the first test, we see that the area of dark blue (lowest pressure) has increased quite a bit as well. The same is true for the modified airfoil, as seen here.

![Figure 25: Modified airfoil at 8 degrees](image)

### 4.2 Side Pods

The goal of designing the side pods is to reduce overall drag, channel airflow to radiators and channel flow around tires. First to reduce the overall drag, the design has curvature to flow air around it.

![Figure 26: Left side pod](image)
The tool used to analyze the design was Solidworks COSMOSFloWork™. The design was to channel flow to the radiators while reducing drag. Also this channeling process acts as a nozzle to accelerate the airflow through the side pod.

![Figure 27: Bottom cut away view of pressure distribution through the left side pod](image)

Figure 27 shows the pressure distribution through the left side pod. As one can see from the image, the pressure entering the side pod is higher than the pressure exiting the side pod. This pressure difference causes the acceleration of the air through the side pod because of the nozzle design. This acceleration of airflow through the side pod increases the overall speed of the car (though only a small amount) because again of the nozzle effectiveness. Though it is only a small addition, it does increase the speed of the car, adding to the overall performance of the car. To channel the flow around the tires the diffuser will come up right behind the radiator forcing the flow over the tires avoiding the turbulent air.

Though the side pods seem to be a small part, the basic design is used in all FSAE designs because if the radiators were out in the open without side pods, this will create not only larger amounts of drag but the chances of damaging an essential element of the car is greatly increases.
4.3. Diffuser

The design of the diffuser is to increase efficiency of flow underneath the car and create a downforce. To analyze the design, CFD modeling was used: COSMOSFloWorks™. A typical velocity of 30 mph was used for the airflow under the car.

As seen from Figure 28, the pressure increases towards the end of the car. This effect causes the air to speed up and places the downforce in the middle of the diffuser. With the current set up, the downforce from the diffuser is located right underneath the seat of the driver. By changing the lengths of the actual diffuser channels (angled part that causes the change in pressure), one can change where the downforce acts. Having the force under the driver balances out the forces created by the front and rear wing. By balancing out the forces the car is more stable when driving. This is most effective during turns. From this we found a prime placement, to have the force directly under the driver seat.

**Figure 28: Underbody diffuser with airflow of 30 mph**

As seen from Figure 28, the pressure increases towards the end of the car. This effect causes the air to speed up and places the downforce in the middle of the diffuser. With the current set up, the downforce from the diffuser is located right underneath the seat of the driver. By changing the lengths of the actual diffuser channels (angled part that causes the change in pressure), one can change where the downforce acts. Having the force under the driver balances out the forces created by the front and rear wing. By balancing out the forces the car is more stable when driving. This is most effective during turns. From this we found a prime placement, to have the force directly under the driver seat.
5. Fabrication and Testing

5.1. Fabrication of 1/6 scale model

In order to do wing testing, we had a rapid prototyping done of the front wing at 1/6 scale. The form of rapid prototyping that was used was Stereolithography. This type of rapid prototyping is good for accuracy and surface finish. To simulate the surface that we used on the full scale wing, we used the same resin and paint used on the front wing.

5.2. Fabrication of Full Scale Body

5.2.1. Rear and Front Wings

The task of fabricating the entire aerodynamic package for a Formula SAE car is no small task. Starting truly from scratch, with no prior aerodynamic wisdom handed down from a previous year’s team makes everything all the more challenging. An in depth and very detailed design and analysis is absolutely crucial. On top of the already very daunting task of design however, is the job of bring all of your innovations and hard work into the physical world. Everyone can appreciate a pretty picture, but pictures don’t win races. You need to know what materials you are going to use, not just for the body shell, but also what is going to hold everything together. Having chosen carbon fiber for its excellent strength properties with relation to its weight and in twill weave with consideration to the limitations in our facilities and its relative ease of manipulation, there are some things that need addressing concerning how go from a loosely woven fabric, to a stiff, smooth, and lightweight body shell.

Their shape being absolutely crucial as to whether or not they function correctly, an airfoil is surprisingly not the most difficult part of a cars aerodynamic package to manufacture. Of course you do need a way accurately to bring an airfoil from conceptual sketch, into real world mold, but
this is the most difficult part. In order to do this, we started by cutting the wing profile itself out of 0.25 in aluminum plate at half scale in hopes it could be used in the creation of a wind tunnel model, which would also serve as experiment to verify the validity of our plan of action. The profile would then be used as a guide for cutting foam using a hot wire. Provided that you are careful to move the hot wire very slowly, and that your hotwire is pulled taught on whatever mechanism is actually holding it, this is a very good way to potentially cut (depending on the length of your wire) a very long mold from foam in the shape of your desired airfoil. It should be noted that the tension of your wire is a critical thing. It must be tight enough to be able to withstand the lateral force it will see as it is dragged through the foam without deforming too much causing the middle of the wire (where the greatest deformation could be observed) to follow a path other than that of your profile.

![Airfoil cutting out](image)

**Figure 29: Airfoil cutting out**

To the right is an image taken while using a CNC Mill to cut our profile from aluminum. The CNC was an obvious choice for the unparalleled ability to machine metal parts that are exactly the same repeatedly that are virtually perfect replicas of what a person need. This is, of course, not the most public friendly way to do it. Few people have access to a CNC Mill, even fewer people know how to use one well, and the accuracy is admittedly much finer than is actually necessary when all of the variables concerning actually finishing the wing are taken into account. However, taking every
step one can towards perfection always yields a better product. See the following image of the finished profile, waiting to be removed from the machine.

![Figure 30: Finished Airfoil](image)

Once the profile was removed from the machine, all that needed to be done was to clean the burred edge, and the profile was ready for use. Using two profiles made in the same fashion, one placed on each side of the foam being used for the mold, we had a good guide to use to cut our molds.

We did run into an issue when trying to cut a long mold all at once. The problem was that the hotwire was too long and difficult to control. At nearly 5ft. wide, even the tightest we could get wire was not tight enough to make the wire follow the profile correctly at the midpoint. So, rather than wasting large quantities of foam simultaneously emptying an already tight team budget, we decided to cut narrower profiles. The idea was to cut the profiles, one by one in two inch increments until there were enough to cover the width of the designed wing. By lining the profiles up with each very carefully, lightly gluing the together, and leaving to dry on a flat even surface, we were able to make a good mold for our wing. This was the same method we used to make our single foil to test in the wind tunnel as can be seen in the picture at the right.
The material laid over this model was not carbon fiber, but fiberglass. With accuracy in mind, we chose another twill weave. The width of the “threads” on the fiberglass fabric was actually closer to half the size of those making up the carbon fiber. By choosing this we hoped to help simulate the half scale surface roughness to get more accurate numerical data.

Although in the beginning of the project the intention was to build wings without a core material, the foam molds became the internal support for our wings. This decision was made because of time restraints. There simply was not enough time to make ribs and spars to support our wings as was originally intended. A disappointment, but all the methods and design researched during the course of this project will be available to next year’s team, which hopefully will let them take what we have accomplished a little farther.

Although the conventional method for making wings tends to be to make a negative mold, and create the top and bottom sides of the wing separately, this was not our plan. Usually the wing is built in halves like this so that the wing spars and ribs can be attached in between the two layers. Now that we had made the decision not to take this road, we could lay each layer of carbon fiber as one sheet. This method yields a wing that is not only stronger on the leading edge, but it looks much better too.
This is the method that we used on all of the wings that make up both the front and back wings. The exception to this generalization is that on the front wing, two base layers of carbon fiber were laid on the leading edge of the main element. These layers extended only back to about the quarter chord point, and were then covered by the top layers that covered the whole wing over. The reason for this was purely for strength. We hoped that in the likely event of someone hitting a cone, the wing would not break. This method was decided no necessary for the rear wing, as it sits far up out of harm's way. All of the carbon fiber after having been laid was vacuum bagged, though it was not cured in an autoclave. The process used is explained in greater detail in the following paragraph.

The endplates on both the front and rear wings were made using lightweight thin foam material that is specifically marketed as core material for composites. Using a large flat surface, the core material was laid out on special mold release film, lightly given an even coat of resin, and covered with a sheet of appropriately sized carbon fiber. Carefully dabbing the surface of the carbon fiber with more resin, we worked all of the bubbles to the edges, then covered the carbon with mold releasing plastic, then resin absorbing material over that. The endplate was then flipped over, and the process was repeated on the other side. The whole thing was then placed in a plastic vacuum bag, and put under suction. Left like this over night, the resin was thoroughly well set, and the edges could be trimmed, and lightly sanded to trim them down to the originally intended shape. After being drilled to support the wings in their final configuration, they were ready for assembly.

5.2.2. Body and Side Pods

Our final design is a very intricate shape. As many people are likely to ask, it wasn’t designed in this shape just to look interesting. In trying to comply with the rules, and working hand in hand with the mechanical engineers building the framework of the car, certain things had to end up a certain way in order to package everything, while still maintaining an “aerodynamically friendly” shape. It was pretty obvious just viewing the SolidWorks model of the body that it was
going to be a challenge to get the material to lay down, and hug the contours of the mold. The true value of vacuum bagging is made very clear when faced with such a task.

Before we could get to the point of laying the carbon fiber however, we had to manufacture a mold. This would be the point generally where, having done a lot of aerodynamic design, most FSAE teams would get in touch with someone with the skill to machine a mold from foam. However, not having the funding nor the connections to have something like this done for us, we had to be creative.

We began by opening our CAD model, and creating planes every two inches, as the foam we planned to use for the molds was 2 inches thick. We then created drawings on each of the planes with lines to an origin in the middle for reference, and printed them out to full scale using a very large printer capable of printing these drawings in 1:1. It should be noted that one should make sure when they set the planes from which they are going to extract a cross section, make sure to start from the large end, and go down. If it is done the other way around, the gaps would have to be filled with something. It is immensely easier to cut foam away, than it is to fill in 2” gaps. After we were sure we had the correct profiles, we cut each of the sections out keeping careful track of which order they were drawn in, and traced them onto our foam board. Then, we cut each section out using both the hotwire and a large floor standing band saw, leaving them a little oversized for good measure. Doing this as a precaution, you leave a little margin for error when cutting the shapes by hand. Once all of the profiles were cut, the next step was draw lines from the point where the origin passed through each profile. By doing this, you can ensure that you are lining your profiles up correctly with reference to each other. As the final preparation before connecting all of the profiles, each profile was sanded down right to the edge of the traced line, making the profile the correct shape.
Now that we had the correct profile shapes, it was time to connect all of the pieces. Using special caulking for bonding foam board, and being sure to line up all the vertical and horizontal origin lines, we connected the profiles one by one.

![Figure 32: Placing the cross sections](image)

The process as it was done on the front body can be seen at the right. During this process we found the best method was to make sure to spread the caulking out across the surface, making as close to an even coat as possible. If this step is not observed, the caulking takes far longer to dry, and you end up using foam to support your wings. To ensure that the profiles were firmly pressed together, each new profile laid onto the mold was very firmly pressed down starting from the middle, and moving outwards. This helped to push any bubbles that might have formed between the two profiles out of the sides, and widens the bonded surface, creating a firm hold. Then, when all of the layers of the mold were put together, and the alignment was checked and confirmed, a wide plate of metal along with a lot of extra weight was set on top, and the mold was left to set overnight.
Once the mold has had time to set, it was time to begin the sanding process. This is the part of our manufacture that took up the most time. Because we did not have the resources to have the mold machine cut, the whole process was done by hand. It is a difficult task to undertake, and must be done very carefully, being sure to not sand too hard (as it would rip the foam up in chunks), and constantly checking for symmetry. When using this method, it is very helpful to mark on the mold the shape that a particular part should be sanded to.
Figure 34: Making the contour line

Side profiles are a big help. By cutting a negative of the profile you are trying to achieve in a particularly tricky area, the quality and accuracy of your work is vastly increased, and if it is symmetric with the other side, you can be far more confident that your mold is well shaped. To the right is an image of the front body mold finished with the nosecone waiting to be sanded.

All of the body molds were made by this method. Then, once the mold was finished being shaped, they were coated with gel-coat to help protect them, and create a surface which could be waxed to ease the removal of the cured carbon fiber. By protecting the molds with gel coat, they stand a better chance of being around long enough to be used by next year’s team.
This method is very time consuming. It’s not as accurate as a CNC. If we were part of a company that designed these types of cars for large scale production, it would be a very inefficient and expensive way to make body molds. Most body molds that are used for making carbon fiber parts for race teams only last for about 40 uses before the mold is too worn (from all the scraping and cleaning) to be used again, and another one must be made.

Despite all of the obvious shortcomings however, it must be said that there exists a certain satisfaction in doing it all by hand. In the end, your back will ache, and you won’t have any fingerprints left, but what you will have is something that you can truly be proud of. Not only will
you have something that is superbly engineered, but you will have something that is beautiful, and completely unique.

Figure 37: Mold of Rear Body

5.2.3. Diffuser

The diffuser was simple to make. Once you have the feel for how to lay carbon fiber without causing it to fray and unravel, it is not such a difficult prospect anymore. With the vast majority of the diffuser being composed of a simple flat plate, the only real concern is how to give it structural rigidity. Even two layers of cured carbon fiber spread out over a large area can be quite flexible. So, we decided to build a framework from balsa, to be laid in between the layers of carbon fiber. The framework was designed to cross all of the mounting points so as to strengthen those spots enough for the purpose, and an extra layer of balsa was added at the points, with special care taken to cross the grain of the two sheets.
As for the diverging part of the diffuser, it was shaped entirely from balsa as can be seen from the image. The curve of the nozzle was cut into the vanes that keep the flow laminar as it re-enters the airstream, and the vanes were then used to bend the upper sheets of balsa into shape. After carefully trimming pieces of carbon fiber to fit the slots, the composite was applied, though not vacuum bagged. It was decided we should just wet-lay the carbon fiber, as the bag would not be able to suck into all of the inner edges without either damaging the balsa frame, or causing the fabric to cure into a shape other than desired.

![Figure 38: Diffuser](image)

6. Overall Results and Conclusions

The use of CFD, Computational Fluid Dynamics, proved to be very useful throughout this project. When deciding the best angle to for both wings, the airfoil was put through different flows at different angles in COSMOSFloWorks™. The angle that proved to be best was an angle of $8^\circ$. This angle has the best lift to drag ratio. To verify the analysis of the CFD testing, wind tunnel testing was done. The results from the wind tunnel testing proved that $8^\circ$ was in fact the best position for the wing. Also from CFD analysis, we were able to calculate roughly the downforce to coefficient of drag of the rear wing. At a typical 30 mph, we calculated to have 22 lbs of downforce with a drag coefficient of 0.05. One can see the results in Table 3.

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The results from CFD for the front wing resulted in about 16 lbs of downforce with a drag coefficient of 0.04. The reason the results of the analysis is slightly lower is because of the shape of the front wing and the duel-element wing. The results can be found in Table 4.

From the results from the rear and front wing we can calculate the relative downforce from the underbody diffuser. This can be calculated by the downforce produced from the underbody diffuser contributes 40% of the overall downforce. From the equation below, the downforce from the diffuser is 53 lbs. Giving an over downforce of 85 lbs for the car. The body also contributes improving the efficiency of the underbody because it encloses the chassis reducing the drag and improves the airflow over the car.

\[
22\text{ lbs} + 10\text{ lbs} + 0.4x = x
\]

The only way to actually test the overall downforce would be to do full scale tests. Placing strain gauges on different parts of the car and do tract tests would be able to support the calculated data. Using LabView to record the results and then compare them to the data that was calculated.
from the CFD analysis. Overall, the addition of the aerodynamic package has increases the performance of WPI's FSAE racecar.
7. Recommendations

To validate the calculated the overall downforce of the car, it is suggested that track testing with strain gauges and pressure transducers. Placing these along each wing, one can measure the high and low pressure along the top and bottom of the wing. The information can be easily recorded using LabView. While time constraints limit testing, it is recommended for future projects to attempt to track test.

Other recommendations would be to rebuild the rear wing to use the endplates as a mounting point. Because one of the goals of this project is to construct molds for future projects for the FSAE car, it should make fabrication easier and designing a more efficient wing should be a goal of future projects. Also, the team wanted to construct the wings so that the angle of attack could be adjusted, again due to time constraints on this project this goal did not get accomplished. By having a variable wing angle, more testing (track testing) can be done to find the optimal angle for each event during the competition.

Having familiarity with CFD modeling would have made this project run smoother as well. One recommendation would be to have WPI offer an introduction course to CFD modeling. Having some background in CFD modeling helped when setting up the model. If one is interested in continuing this project, an independent study in basic CFD modeling would probably be most beneficial.

Lastly, working closely with the FSAE team is always recommended. For any project having a strong communication link between the projects makes designing and building run smoothly. Discussing changes in designs and keeping up to date with any changes and news about the car, makes for completion of the car much easier. Also having the deadlines and keeping to the deadlines
set forth help in the completion of the car. Following a timeline of goals, the team can prove to be more efficient with design, construction and testing of the car.
References


Appendices

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