Bicycle Frame Shape and the Effect on Performance
An aerodynamic study of the Trek KVF Frame

An Undergraduate Honors College Thesis

in the

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1. INTRODUCTION

Throughout the history of cycling, there have been constant improvements on technologies. The driving force behind these improvements in the cycling world has mainly been competitiveness. Most improvements through the years have been modifications to layout of the mechanisms on the bicycle. This includes overall shape of the bike, design of a drive train, and material improvements. Once riders began to push themselves faster, aerodynamic drag became a problem. The rider and his machine must work harder to push through the air the faster they move. Once cycling engineers realized this problem, changes were made to allow the rider to have a smaller frontal surface area, therefore reducing the overall aerodynamic drag force.

Eventually, these engineers began to look at the actual cross sectional shapes of the bicycle frame itself. Engineers at Trek claim to have created the world’s most aerodynamic bike allowed by international racing regulations. The purpose of this thesis is to either confirm Trek’s claims or disregard their scientific claims as a marketing tool.

For my research, I have chosen to use two models of Trek bicycles of which I have physical access to, along with a few other theoretical frame shapes. I began by taking accurate measurements of cross sections and compared these to published information. I then recreated sections of the bike frame and used SolidWorks© Flow Simulation software to calculate the drag forces. I then go on to discuss the validity of Trek’s claims.
2. CYCLING AERODYNAMICS

2.a. What is aerodynamics?

Aerodynamics is a sub field of fluid mechanics. Fluid mechanics is the study of the motion of a fluid substance and the interactions of that fluid on any object the fluid comes into contact with. Fluid dynamics can basically be divided into two different areas of study; internal flow and external flow. Internal flow is the study of fluids through an enclosed space, such as a pipe or duct. This form of flow study comes into use when designing HVAC systems along with any type of water or oil distribution. The other type of flow is external flow. This is the flow of a fluid around a solid object. Industries concerned with this are mainly aerospace and automotive. Obviously, airflow around a vehicle has a large impact on the performance of that vehicle. In the aerospace field, external flow around wings is what created the large amounts of lift needed to get the aircraft into the skies. In the automotive industry, external flow of air around the vehicle has a large impact on the fuel efficiency and even the speed of the vehicle. This is where we can see the relation to the cycling industry as well. This thesis will mainly be concerned with the external flow analysis of many different bicycle frame shapes, specifically, how that shape will change the way the air behaves when flowing around and interacting with the frame.

2.b. Cycling Aerodynamics

Before we begin examining the airflow around the bicycle, we must determine why this is relevant to the cyclist. For the sake of our calculations, the
cyclist will effectively be an engine. This “engine” will be capable of producing a constant energy output. This energy output is then transferred through a drive train to the rear wheel of the bike. Depending on the goal of the rider, these drive trains can have very different arrangements. Your average bicycle makes use of a chain drive with varying speed increase gear ratios. This energy is then transferred from the tire to the road. For the application we are particularly examining, this road will be flat and straight. This is very typical of the average time trial or triathlon course. Once up to speed, very small amounts of energy are needed to keep speed without air resistance. While accelerating, energy is used to increase the inertia of the vehicle. Newton’s first law tells us that once speed is achieved, in the absence of external forces, the bicycle should remain at that speed. So assuming we have a constant input of energy from our rider, there are significant losses occurring. At first glance, we can examine a simple free body diagram of external forces in the horizontal direction to see where these losses are occurring.

Figure 1: Visualization of external forces acting on bicycle in X direction.
As can be seen, losses are mainly occurring from the rolling friction at the tire and road interface, as well as the force of friction between the air and the bicycle and rider. We can determine the rolling resistance using a simple formula:

\[ F_R = k_R N \]

Where \( F_R \) is the rolling friction, \( k_R \) is the rolling friction coefficient, and \( N \) is the normal force. The rolling friction coefficient is an experimentally found value that can be found in many published sources. Values for these coefficients can vary slightly but as can be seen, they are so small when compared to the normal force that these small fluctuations have little effect on the total. Exact measurements will be seen later when examining actual data, but the following serves to show how small rolling friction is compared to air resistance.

\[ k_R = 0.003 \]
\[ N = 180 \text{lbf} \]
\[ F_R = 0.54 \text{lbf} \]

To see just how little this force is compared to the whole of the losses, the power produced by the rider must be converted into an instantaneous force. Using average data from myself, we can assume the power output to be around 200 watts at a
speed of 18 miles per hour. We can then convert this to an instantaneous force with the following method of dimensional analysis.

\[ \text{Power} = \frac{\text{force} \times \text{distance}}{\text{time}} = \text{force} \times \text{velocity} \]

200 watt = 147.5124(lbf*ft)/s
18 mph = 26.4 ft/s

\[ F = 5.588 \text{lbf} \]

As you can see, rolling resistance only accounts for around 9% of the total loss of energy in the system. That only leaves minor losses occurring within the drive train, and wind resistance. But what exactly is wind resistance and what steps can be taken to reduce this?

2.c. External Flow

As mentioned above, external flow constitutes all fluid flow analysis occurring when a fluid flows around a solid body. For this type of flow, several concepts need to be addressed. The first of these is fluid velocity. In external flow, the fluid velocity will range anywhere from 0 at the surface of the object, and the free stream velocity. That is, the velocity of the approaching fluid. The velocity of the fluid is important to our calculations because energy must be used to slow the oncoming air to zero velocity (with respect to the cyclist). The less impact the cyclist
has on changing the velocity of the oncoming air, the better. Velocity also plays another important role. This role can be stated simply with the Bernoulli equation. This is a simplified equation that can be used when viscous effects of the fluid are relatively small and the fluid can be assumed to be steady and incompressible. For the purposes of this thesis, these statements hold true because of the low speeds at which the cyclist operates. In its simplest form, the Bernoulli equation is a statement that when a fluid’s velocity is increased, pressure within the fluid decreases. Conversely, when a fluid’s velocity decreases, pressure within the fluid increases. This brings us to another concept that contributes to drag force, pressure. The difference in velocity in front of and behind the object in the fluid flow causes a pressure differential. This causes a net force to act on the object, which opposes the direction of motion. This brings us to another factor, friction. Friction only affects the fluid in the region of flow closest to the object. In this region, known as the viscid region, fluid viscosity interacts with the surface roughness of the object, causing friction.

2.d. Boundary Layer and Flow Separation

Now that the principles affecting drag have been discussed, we can go into depth on them individually. The first of these is boundary layer mechanics. This is the concept that in effect governs many other factors contributing to drag. So what exactly is a boundary layer? When fluid flows around an object, the velocity profile ranges from zero velocity at the surface to the free stream velocity. This creates a velocity gradient, which can be seen below:
In the region closest to the surface of the object, where the flow is slowest, is known as the viscid region. In this region, the viscosity of the fluid is significant to the flow characteristics. This is what causes the fluid to exert friction forces on the surface of the object. At some point in the fluid velocity profile, the viscosity of the fluid becomes insignificant to the flow characteristics. This region is known as the inviscid region and is the area where the flow can be analyzed by simplified flow equations. The point at which this transition between regions occurs is known as the boundary layer. The boundary layer affectively will increase the thickness of the object because of the behavior of the fluid within the viscid region. Therefore, engineers trying to reduce drag forces will try to bring the boundary layer as close to the object as possible. In most cases, the boundary layer height will increase as the object curves away from the flow. The point at which this happens is known as the point of flow separation. This can be seen below in an actual simulation from this thesis.
Figure 3: SolidWorks© visualization of flow trajectories. Simulation is air flowing at an angle of 10 degrees over the Trek KVF model. Trajectories show separation point.

This area of separation creates a low pressure region, which contributes to the pressure drag. If the point of flow separation can be placed as far back on the object as possible or better yet, eliminated, then drag can be greatly reduced.

2.e. Velocity and Pressure

Let us recall Bernoulli's equation, which states that in a region of steady, incompressible, inviscid flow, that pressure will decrease as fluid velocity increases and pressure will increase as velocity decreases. This can be seen below when both points along a streamline are analyzed at the same altitude:

\[ \frac{P_1}{\rho} + \frac{V_1^2}{2} = \frac{P_2}{\rho} + \frac{V_2^2}{2} \]

Therefore as an engineer trying to reduce the total force opposing motion, one must try to have as little impact on the free stream velocity as possible. Ideally, the velocity of the fluid in front of the object should be increased. The fluid behind the object should be slowed, without separating and causing a vacuum. In reality, when
the object comes into contact with the oncoming fluid flow, the fluid will slow at the leading edge. This causes a pressure increase. In most object geometries, flow will separate at a point along the streamline, causing a point of low pressure. This is known as the wake of the object and results in a net force opposing object motion through the flow. Streamlining the shape of the object can reduce this pressure drag. This in effect causes the flow to remain attached. So while there will still be a slight pressure increase in front of the object, there will be no vacuum behind it, greatly reducing drag. Pressure drag in fact is the leading cause of drag force in most situations.

2.f. **Friction Drag**

Every surface has a roughness to it at a molecular level. This surface roughness interacts with the viscosity of the flowing fluid. This interaction between the molecules causes friction, which will oppose the motion of the fluid over the surface. This occurs over the entire surface of the object in contact with the fluid and results in a net force opposing motion through the fluid. In objects where streamlining has reduced most of the pressure drag, friction drag constitutes a large portion of the total drag on the object.

2.g. **Total Drag Force**

All of these factors contribute to one overall drag force, which will need to be minimized. Because the individual components of drag are very difficult to analyze individually, it is conventional to determine the overall drag and express this in one
formula relating drag force, fluid density, fluid velocity, and frontal surface area. All of these are related to each other along with a drag coefficient, which is a dimensionless number. The aerodynamic drag on an object is expressed in the following:

\[ F_D = \frac{1}{2} \rho V^2 C_D A \]

where

- \( F_D \) = Force of Drag
- \( \rho \) = Air Density
- \( V \) = Flow Velocity
- \( C_D \) = Coefficient of Drag
- \( A \) = Frontal Area

This formula provides a way of determining experimentally the performance of certain geometries of objects, which must be exposed to fluid flow.

3. CYCLING IMPROVEMENTS

3.a. History of Improving Cycling Performance

The first bicycle was the result of several innovations. One of these was a two-wheeled mechanism called a Velocipede. It was basically just two wheels and a
seat made entirely from wood. The rider could propel himself by pushing the ground with his feet.

![Figure 4: Artist representation of a Velocipede.](image)

It was a very primitive form of the bicycle but it was faster than walking because more energy was conserved with the use of wheels. In 1870, the Highwheeler appeared. This is the famous design that consisted of a large front wheel with pedals attached directly to the wheel. The high center of gravity made these difficult to ride, but also allowed for greater speed due to the large radius of the powered wheel.
Throughout the late 1800s, additional mechanical improvements such as caliper brakes and ball bearings made cycling much safer. In the 1890s, the safety bike was invented. This featured a chain driven rear wheel that still remains in existence today. The gears involved in the chain drive also allowed for much higher speeds. It wasn’t until the 1930s that the modern cable derailleur was invented. This allowed cyclists to change gears by “derailing” the chain onto a different gear. These different gear ratios allowed for much higher speeds than before while still being able to ride comfortably on inclines. Eventually, the mechanical increases began to reach a limit, which could only be surpassed when improvements were made in other areas.

This is where aerodynamic improvements came into play. First improvements focused on rider position. By slightly adjusting the angle of the rider’s waist, the frontal area can be greatly reduced. Some improvements that
helped with rider position include the drop handlebars as well as the even more aerodynamic “aero bars” common today in time trial and triathlon racing, where drafting is illegal.

3.b. Trek and Use of Airfoils in Cycling

It was during these times of aerodynamic improvements that airfoils began to be implemented into the designs of bike frames. However, racing regulations prohibit the use of traditional airfoils. The resulting design would be too thin compared to the length of the cross section. This design would not provide enough stiffness and strength for the cyclist. This could potentially endanger the cyclist. There must be a way to implement an aero shape while remaining within the regulations and safety requirements.

Trek Bikes claims to have found a solution. The design implements an airfoil shape that is cut off at the regulated length to width 3:1 ratio. This design is said to create a virtual airfoil behind the frame that will allow air to flow around the frame exactly as it would flow around a traditional airfoil. This new frame shape is said to be more efficient than traditional bike frame shapes. Let us look at a few features that make this possible. Revisiting the causes of aerodynamic drag, we will look at individual reasons why the KVF is the best shape for competitive cycling.

The first of these causes mentioned was that of boundary layer and separated flow. Things that can be done to reduce drag are keeping the boundary layer as close to the object as possible, for as long as possible. Below we can see two examples of boundary layer separation.
Figure 6: Velocity cut-plot showing boundary layer separation. Simulations are air at an angle of 10 degrees on the Trek KVF model and NACA 0018 airfoil.

Notice that separation occurs around the same spot relative to the origin, but on the KVF, because it is shorter, the separation occurs near the back of the frame. This means that the vacuum has less area to pull the frame.

Next is the pressure drag caused by a velocity gradient. This is very noticeable between the conventional tubular frame and the KVF.

Figure 7: Pressure cut-plot showing pressure distribution. Simulations are air at angle of 0 degrees and 10 degrees, acting on tubular frame and Trek KVF, respectively.
Notice the huge amount of pressure increase in front of the tubular frame compared to the KVF. Also note that the area behind the KVF is around ambient pressure, while the area behind the tubular frame is creating a vacuum effect. This is the main reason why the KVF and airfoil performed so similarly.

4. CFD

4.a. What is CFD?

CFD stands for Computational Fluid Dynamics. It provides a way for designers to test the fluid dynamic properties of a certain geometry without needing to build a physical model. Modern computers are able to run thousands of calculations a second in order to determine flow properties such as velocity, pressure, flow direction, and even the forces exerted by the fluid on a surface. All of this is done by properly entering boundary conditions and running a simulation. For this thesis, I used SolidWorks© Flow Simulation 2012.

4.b. Simulation Procedure

The procedure for creating a valid simulation involves three basic parts. The first is pre simulation setup, creating the simulation, and finally post simulation result generation. Each of these steps must be done with extreme care and detail so that the results are as realistic as possible. Ideally, we should be able to run a simulation on a CFD program, then take that same object and test it in an accurate
wind tunnel and receive the same results. For this thesis, the only wind tunnel I had access to was the Mechanical Engineering wind tunnel used for Labs. Although this tunnel can give a basic approximation of the forces generated, the vibrations caused by the fan cause too much variation in the readings of such small forces. Therefore, CFD software proved to be a very valuable resource and was therefore used for the majority of calculations; While the wind tunnel basically served to validate that the CFD software ran the simulation correctly.

4.c. Pre-Simulation Set-Up

Before any simulations can be run, we must create accurate models of the objects to be tested. For this thesis, an airfoil with the same dimensions as the Trek Frame shape was chosen and modified. This happened to be the NACA 0018 symmetrical airfoil with a 9.9% increase in cross sectional width. In order to achieve this shape, an online two dimensional plotter was used to generate points.
Figure 8: Online Airfoil Plotter used to create profile of modified NACA 0018 airfoil for use on Trek KVF model.

Once these points were generated, they can be imported into SolidWorks© as a curve using the following method.

1. Save points in an Excel file with the extension .txt
2. Open SolidWorks© and create a new part.
3. Go to insert => curve => curve from XYZ points.
4. Open the file containing the points.
5. SolidWorks© will now create a curve through the points. To extrude this curve into an actual part that we can use we must turn the curve into a sketch.
6. Select the curve and create a new sketch in the plane containing the curve.
7. Select the curve and select tools => sketch tools => convert entities
8. Exit the sketch

Now that the sketch of the airfoil is created, it can be extruded to the desired length. For this thesis, calculations were run using 10in segments of each shape. For the full airfoil, the part is finished. For the Trek KVF frame shape, we must cut the tail end of the foil to the proper dimensions. For the Trek 2.1, the frame shape is essentially a circle with a slightly more oblong shape. This is created using conventional methods.

Now that we have our models, we can begin the process of setting up a simulation. We will first open the part to be tested. In order to run a simulation, Flow Simulation must be added in.

1. Go to tools => add ins => Flow Simulation 2012

2. Flow Simulation will be added to the menu bar.

4.d. Creating a Simulation

Now we can begin to set up the flow simulation project. In order to do this, we can use the flow simulation Project Wizard to create the project.
1. Click flow simulation => Project => Wizard. This will open up the Wizard window. Here we can name the project.

![Figure 9: Project Wizard for SolidWorks© Flow Simulation.](image)

2. Next we can walk through the wizard. Choose the system of desired units.

3. Select external analysis. Also exclude internal cavities from analysis.

4. Choose the fluid. Air is a pre-defined fluid.

5. Set the wall roughness to that of stainless steel ~1 micro inch.

6. The air properties are set at STP. We choose the velocity to be 18mph (my average speed in my last race.

   - For an angle of attack of zero degrees, velocity is entered into the X direction only. For angles of 5, 10, and 15 degrees, we simply calculate the
X and Z components of 18mph at those respective angles and enter the values here.

7. Set the result resolution and minimum wall thickness. It is important that this is set at least as small as the thinnest portion of the model so that results can be accurate.

8. Finish the Wizard.

We now have our project created. From here we can see that a computational domain has been placed around the model. The larger this domain, the longer the calculation will take. We will choose a size that will allow the object to be properly analyzed while still performing relatively quick calculations. It is also at this point we will set our goals. Because we are calculating drag, we only need forces acting on the object along the X axis. There are several forces that can be calculated here. We will choose global goals (affecting the entire model) of force in the X direction, force normal to the surface in the X direction, and friction force in the X direction. Because the models are being analyzed at such low speeds relative to those of high speed aircraft, friction against the surface of the frame will play a significant role in the total drag force. We may now run the simulation.

4.e. Running Simulation

In many CFD programs, we must first set up the algorithms used. However, with SolidWorks© Flow Simulation 2012, the project wizard will automatically choose the mathematical processes based on the geometry, fluid chosen, and
conditions of pre defined fluids. This makes the engineer’s job very easy for this portion of the simulation. We simply hit “run” and a flow simulation window will pop up. It begins processing the information immediately. First creating a volumetric mesh to analyze the flow at individual differential segments. It will then run through as many iterations as it needs to converge on the goals we have created. When the calculation is finished, the window will display the following.

![Screenshot of SolidWorks© Flow Simulation 2012 Solver. Solver status is “Solver is Finished”](image)

Figure 10: Screenshot of SolidWorks© Flow Simulation 2012 Solver. Solver status is “Solver is Finished”.

4.f. Result Generation

Once the Solver has finished, we can see the results. It would be impossible to view all of the results at once because this would very quickly become a jumbled mess of colors and contour lines. SolidWorks© has an easy way around this
problem. We can insert individual “cut plots” to visualize things such as velocity, pressure, temperature, etc. These cut plots show a visual representation of the fluid in a plane. We can see this below.

Figure 11: Cut-plot of velocity of air at an angle of 0 degrees acting on Trek KVF model.

SolidWorks© can also show flow trajectories to give us an idea of the flow directions. We can either view them in a plane or view any flow path that interacts with the surface. These can even be animated to give a realistic visualization of the entire process. We can see this below.
Figure 12: Flow Trajectories in a single plane. Simulation is air at 0 degrees on Trek KVF.

Figure 13: Flow Trajectories along surface. Simulation is air at 10 degrees on NACA 0018 airfoil.
These all help to visualize the simulation so that we can understand what is going on when the results are examined analytically. So now we move onto the actual data. When the simulation was set up, recall that we set surface goals for the objects in the X direction. We can gather these results by clicking on goal plots in the tree. It will then export the information to excel. The results will be something like this:

Figure 14: Exported data from Solidworks© Flow Simulation global goal calculation.

As can be seen, the forces here are very small. This is due to the fact that the object is small and aerodynamically shaped while being tested at a relatively low speed. Although this is seemingly insignificant when compared to the drag forces you would expect to be experienced by the body of the cyclist, over the course of a race several minutes can be taken off of the total time.

5. DATA

5.a. Drag Force

When determining exactly how beneficial the changes in design to the frame shape were, the first step was to determine the forces experienced by each frame shape in similar conditions. The only variable changed in each scenario is the
geometry of the model. For all tests, forces were calculated along the X axis. The reasoning being that this is the direction of the force, which will resist motion, therefore counteracting the energy input from the cyclist. However, when cycling, often there is a slight amount of cross wind. This means that the angle of the air as it comes into contact with the frame will not always be 0 degrees. The claim by Trek is that in normal racing conditions, i.e. side winds, the KVF shape is more efficient than an aerodynamically shaped symmetrical airfoil. The results can be seen below.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Wind Angle</th>
<th>Wind Speed(mph)</th>
<th>Drag(lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Airfoil</td>
<td>0</td>
<td>18</td>
<td>0.03125049</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>0</td>
<td>18</td>
<td>0.03400351</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>0</td>
<td>18</td>
<td>0.09746804</td>
</tr>
<tr>
<td>Full Airfoil</td>
<td>5</td>
<td>18</td>
<td>0.03363148</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>5</td>
<td>18</td>
<td>0.03541722</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>5</td>
<td>18</td>
<td>0.0982002</td>
</tr>
<tr>
<td>Full Airfoil</td>
<td>10</td>
<td>18</td>
<td>0.03750059</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>10</td>
<td>18</td>
<td>0.03690534</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>10</td>
<td>18</td>
<td>0.09847475</td>
</tr>
<tr>
<td>Full Airfoil</td>
<td>15</td>
<td>18</td>
<td>0.04360187</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>15</td>
<td>18</td>
<td>0.0389887</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>15</td>
<td>18</td>
<td>0.09865779</td>
</tr>
</tbody>
</table>

Table 1: Drag force in X direction of all models and wind angles.
Figure 15: Drag force acting on 10 inch segments of frame as it corresponds to angle of attack. All simulations represented.

As can be seen, the airfoil is more aerodynamic at straight angles but as the cross winds increase, the KVF will become more aerodynamic than the NACA 0018 airfoil. This can be seen closer below.
Figure 16: Drag force acting on 10 inch segments of frame as it corresponds to angle of attack. Only NACA 0018 and Trek KVF represented.

As can be seen, once the angle of oncoming air reaches around 9 degrees, the KVF shape is more aerodynamic. This corresponds to a side wind of only 2.8mph, a very reasonable speed during normal racing conditions.

5.b. Coefficient of Drag

The next step in calculations was to find the coefficient of drag for each shape and angle. The equation for the coefficient of drag is taken directly from the drag force equation.

\[ C_D = \frac{2F_D}{\rho AV^2} \]
Because we already have the force from the simulations, all that must be done is to obtain the air properties at which the simulations occurred. This just leaves the frontal area of the object being tested. This can be calculated by measuring the objects in SolidWorks®. Once all this has been done, the drag coefficients can be calculated.

![Drag Coefficient vs Angle of Attack](image)

**Figure 17:** Drag Coefficient as a function on wind angle. All simulations are represented.

Once again, the KVF shape overtakes the airfoil at around 9 degrees.
Figure 18: Drag Coefficient as a function on wind angle for Trek KVF and Airfoil only.

5.c. Area

Now that all the information is available, we can begin calculating how much this small difference in force can affect a race. All calculations up to this point have been with a 10 inch segment of frame. In order to obtain accurate results, this must be expanded over the entire bike. To do this we must find the frontal area of each bike by factoring in the height. This is an approximation but because it will be applied to all shapes, any uncertainty will be the same, therefore not affecting the final result. Similarly, this bike cannot compete alone. A rider must sit atop the bike, therefore having his own drag forces associated with him. However, once again the
rider will be the same rider in each instance so only approximations must be taken into account. For our purposes, the rider will be 5'9" with a mass of 180 lbm. While seated on the bike he will have approximately 4 square feet of frontal area and a drag coefficient of 0.9. This is a value that has been experimentally determined by professional race teams.

Our first step is to calculate how much of the total area is taken up by the bike. To do this we simply find a percentage.

\[
\frac{A_b}{A_t} = \frac{A_b}{A_b + A_c}
\]

Which yields the following results.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Ab/At</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Airfoil</td>
<td>6.317%</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>6.317%</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>9.836%</td>
</tr>
</tbody>
</table>

Table 2: Area of the bike compared to the total area.

5.d. Power

Now that the frontal area is known, we can calculate the power needed to overcome the aerodynamic forces on both the bike, the rider, and the total. We simply use the following equation for power.
\[ P = \frac{C_d \rho AV^3}{2} \]

Yielding the following results.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Airfoil</td>
<td>0</td>
<td>0.111</td>
<td>2.97454142</td>
<td>0.00532629</td>
<td>2.92143964</td>
<td>77.14346579</td>
<td>0.14026084</td>
<td>2.95508743</td>
<td>80.07292521</td>
<td>0.14558714</td>
<td></td>
</tr>
<tr>
<td>Trek KVF</td>
<td>0</td>
<td>0.121</td>
<td>3.16753202</td>
<td>0.00579551</td>
<td>2.92143964</td>
<td>77.14346579</td>
<td>0.14026084</td>
<td>2.95544045</td>
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<tr>
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<td>4.08729617</td>
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<td>86.39177348</td>
<td>0.1570395</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Drag force and power needed to overcome aerodynamic drag for all frame shapes and wind angles.

5.e. Speed

We will now assume that because the rider is the same in each instance, his power output will be the same. Because the rider will have less drag while riding the KVF and theoretical airfoil bike, the speed can be adjusted so that the power output is the same as that on the Trek 2.1. To do this, the coefficients of drag will also be changing along with the forces. To do all of this simultaneously we can use Excel’s Solver function. This will give us the new speeds.
### Table 4: Speeds assuming constant power output equal to that of the Trek 2.1 after Excel Solver has converged to corrected speeds.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Wind Angle</th>
<th>ft/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Airfoil</td>
<td>0</td>
<td>29.2209</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>0</td>
<td>29.1937</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>0</td>
<td>28.5800</td>
</tr>
<tr>
<td>Full Airfoil</td>
<td>5</td>
<td>29.2206</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>5</td>
<td>29.2030</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>5</td>
<td>28.5958</td>
</tr>
<tr>
<td>Full Airfoil</td>
<td>10</td>
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</tr>
<tr>
<td>Trek KVF</td>
<td>10</td>
<td>29.1970</td>
</tr>
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<td>10</td>
<td>28.6017</td>
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<td>29.1368</td>
</tr>
<tr>
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<td>29.1822</td>
</tr>
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<td>28.6057</td>
</tr>
</tbody>
</table>

5.f. **Time**

Now that the speed, force, and power have all been adjusted to assume a constant power output from the cyclist, we can finally see what this means to the cyclist in terms of time. To do this we will use a 100 mile race, or century. It is basically the marathon to cycling. To determine race time, we just use the adjusted speed and the distance of the race. This will give us the following results.
Table 5: Time to complete 100 miles in minutes. Time corresponds to speeds at constant power output of Trek 2.1.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Wind Angle</th>
<th>Time in 100 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Airfoil</td>
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<td>301.1540937</td>
</tr>
<tr>
<td>Trek KVF</td>
<td>0</td>
<td>301.434883</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>0</td>
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</tr>
<tr>
<td>Full Airfoil</td>
<td>5</td>
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</tr>
<tr>
<td>Trek KVF</td>
<td>5</td>
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</tr>
<tr>
<td>Trek 2.1</td>
<td>5</td>
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<tr>
<td>Trek KVF</td>
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</tr>
<tr>
<td>Trek 2.1</td>
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</tr>
<tr>
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<td>301.5535409</td>
</tr>
<tr>
<td>Trek 2.1</td>
<td>15</td>
<td>307.6315259</td>
</tr>
</tbody>
</table>

With the time of the 2.1 taking longer than the KVF by these amounts, given wind angle.

Table 6: Time in minutes that the Trek KVF completed the 100 mile race before the Trek 2.1 completed the race at all wind angles.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Time saved(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
<td>5</td>
<td>6.398347394</td>
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<td>10</td>
<td>6.272801142</td>
</tr>
<tr>
<td>15</td>
<td>6.077985035</td>
</tr>
</tbody>
</table>

As can be seen, this simple adjustment in frame shape can save around 6-7 minutes during a race. For the competitive cyclist, this can make the difference between placing first and not even making the podium.
6. Conclusion

The purpose of this thesis was to design tests that would either prove or disprove the statement made by Trek Bikes that claims they have created the world's fastest race bike. Given the resources available to me and with the knowledge gained throughout the Mechanical Engineering curriculum, I have shown this statement to be true. Although I had no access to other manufacturer's bicycle models, the Trek KVF frame shape used on the Speed Concept series was shown during tests to outperform a perfect airfoil shape. Taking influences from both the automotive and aerospace industries, Trek has created a frame that can give competitive cyclist a substantial advantage over their opponents.
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