

Product Design and Development of an Aerodynamic Hydration System for Bicycling and Triathlon

by

Mark Cote

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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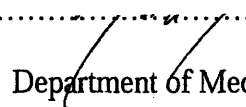
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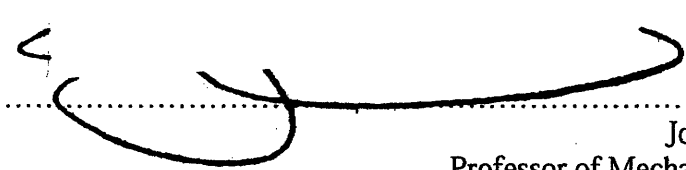
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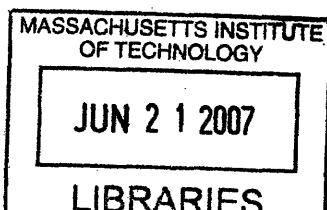

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ARCHIVES

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SYSTEM FOR BICYCLING AND TRIATHLON

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ABSTRACT

Proper hydration and aerodynamic performance are both essential needs of a competitive cyclist or triathlete. Several aerodynamic systems have been developed for use on bicycles but few have been designed to be truly aerodynamic or easy to use. This project focused on the design and development of a frame mounted hydration system for cycling and triathlon that offered improvements in usability and aerodynamic performance over the current market solutions. A wind tunnel test validated a viable location on to place the fluid reservoir. Product specifications were derived from consumer needs and concepts were generated to fulfill those needs. Several iterations of CAD models of the entire product were made. The resulting product, a top tube mounted reservoir with a drinking tube and tri-leaf check valve for re-filling the reservoir while riding will be prototyped by the author over the summer of 2007.

Thesis Supervisor: Dr. Kim B. Blair
Title: Research Affiliate

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BIOGRAPHICAL NOTE

The author, Mark Cote (Mechanical Engineering BS '07; Course 2A), focused his undergraduate coursework around product development and entrepreneurial studies. His personal research, led by Dr. Kim Blair, focused on aerodynamic performance in cycling and triathlon. He completed four years of research at the Wright Brothers Wind Tunnel researching aerodynamic performance on athletes and cycling equipment.

During his undergraduate years, the author completed internships at Cervelo Cycles in Toronto, Ontario, and Specialized Bicycle Components in Morgan Hill, California.

He is an avid cyclist and triathlete and competed with both the MIT Cycling Team and MIT Triathlon Club.

Noteable Achievements:

DeFlorez Design Award Winner for “outstanding ingenuity and creative judgment”

(Awarded for the product design outlined in this thesis)

MIT IDEAS \$5,000 Winner as part of Team Bluesteel

2006 Mechanical Engineering Sontheimer Design Award

2005 2.007 Mechanical Engineering Design Contest

1.0 INTRODUCTION

1.1 *Cycling and Triathlon Explained*

The sports of triathlon (consisting of swimming, cycling, and running legs) and road cycling are two quintessential examples of endurance athletic sports. While competing in these sports, athletes have very discrete nutrition and hydration needs. During races over thirty minutes, electrolytes and fluids need to be replenished for the athlete to perform at his or her top level.

While racing, cyclists require at least sixteen to twenty-four ounces of fluid per hour¹. Thus, depending upon the athlete and event distance, up to one hundred ounces of fluid will be consumed during the cycling leg of a triathlon. Though there is an obvious need to replace fluids while riding, it is challenging and takes focus away from controlling the bicycle.

This is especially true for triathletes who typically ride in an aerodynamic tuck using special handlebars called “aerobars”. These bars incorporate elbow pads that put the athlete in a more comfortable and streamlined position. This position, as shown in *Figure 1*, makes it hard to reach for frame-mounted water bottles while riding. Due to this challenge, most athletes do not replenish liquids as often as they should.



Figure 1: Triathlete riding with aerobars in an aerodynamic tuck using a traditional frame-mounted water bottle.

Triathletes need a hydration system that allows them to ride in this aerodynamic position, easily consume liquids without the use of their hands, and improves their overall performance while racing.

1.2 Aerodynamics in Cycling and Triathlon

Cycling and triathlon are performance-based sports and their elite participants are focused on using the best performance products available. As with other endurance sports, performance gain is usually found by decreasing forces acting against the athlete's forward progress. On a typical cycling course, the largest resistive force acting on the athlete is aerodynamic drag. For example, a cyclist riding at 48 kph (30 mph) expends about 76-90% of his or her power output just to overcome aerodynamic drag. Roughly 25% of this drag is due to the rider's equipment² (the rest is due to the athlete's body).

Manufacturers of cycling equipment have recognized the effects of improving aerodynamic performance over the past two decades and many products have been designed specifically around aerodynamic theory. Generally, aerodynamic frames and wheels the most have had the largest market presence in the aerodynamic cycling product niche. The author notes that over the past few years, aerodynamically designed helmets have become more popular in the cycling world and have become very common at triathlon events. *Figures 2 and 3* show traditional products versus aerodynamically optimized products for bicycles and helmets, respectively.

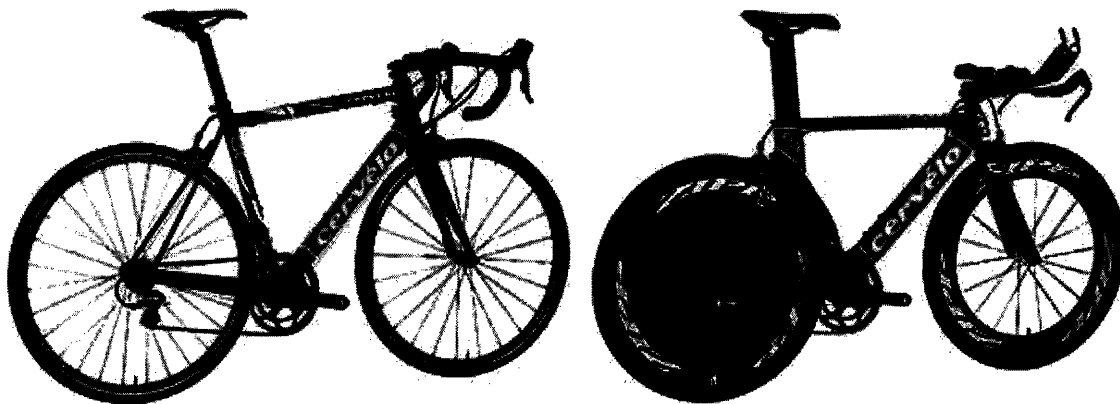


Figure 2: Example of a traditional style road bike (left) versus an aerodynamically designed bike (right). Both bikes are made by Cervelo Cycles.



Figure 3: Example of a traditional style road helmet (left) versus an aerodynamically designed helmet (right). Both helmets are made by Specialized Bicycle Components.

1.3 Aerodynamic Water Bottle Design: The Motivation

Since triathlon bikes range in cost from \$1,500 - \$10,000 USD, cycling companies generally focus on the bikes alone and often overlook the small details of the athlete's experience. Most companies focus on frame sales and high-end aerodynamic components needed to compete in the high-end market – features such as aero wheel sets and carbon composite frames. Despite the high-tech look of these products, few are designed to optimize aerodynamic performance for the athlete.

The best of these bikes are the aerodynamically engineered carbon fiber “super” bikes ridden in races like time trials at the Tour de France. Despite the narrow profiles of these bikes (tubes as narrow as 25 mm in maximum width), large cylindrical water bottles with diameters of roughly 75 mm are mounted to the frames. *Figure 4* shows a 620 ml (21 oz.) water bottle and cage mounted to an aerodynamic frame.



Figure 4: A water bottle and cage mounted to the downtube of an aerodynamic bicycle frame.

Previous unpublished research in the MIT Wright Brothers Wind Tunnel has shown that the performance improvement due to narrow aerodynamic bicycle frames is entirely lost when cylindrical water bottles are mounted to them² (these wind tunnel tests were completed with an athlete on the test bicycles). This data suggests that the companies spending large sums of money to make athletes faster should consider the aerodynamics of the entire equipment and rider system when designing individual products.

Wind tunnel testing conducted by the author in early 2004 identified an ideal location on the bike for storing water. While using glycol smoke and tufts of yarn to visualize flow over a bike and rider during a test, the author noticed a low-pressure volume behind the handlebars. Due to the large cylindrical shape of the steerer tube and cable housings, a large amount of separated flow resulted behind the stem and handlebars. Based upon aerodynamic theory, filling in this volume with a smooth, rigid container should contribute some pressure recovery in this wake region. When adapted to the needs of the cyclist and triathlete, a container here could offer improved aerodynamics versus a traditional cylindrical water bottle and allow for the storage of greater than 600 ml of liquid.

As a mechanical engineering student focused on product design, the author believed an aerodynamic water bottle to be a perfect design project. The relative engineering simplicity allowed for a quick product development cycle and the huge demand from the triathlon and cycling market made it a prime product for possible market launch.

2.0 VALIDATION OF AERODYNAMIC CONCEPT

Due to the cylindrical shape of the steering tube, handlebars, cable housings, and stem, the flow in this volume is generally separated or turbulent airflow. A simple aerodynamic test was employed at the MIT Wright Brothers Wind Tunnel to validate the theory that this low-pressure system caused a significant amount of pressure drag on the bicycle. The objective of this experiment was to empirically measure the pressure drag caused by these bicycle parts and generally understand the pressure gradient behind the steering tube. The following section outlines the experimental theory, procedure, and

results. *Figure 5* shows a labeled front end of an aerodynamic bicycle. *Figure 6* shows the area of interest for this experiment.

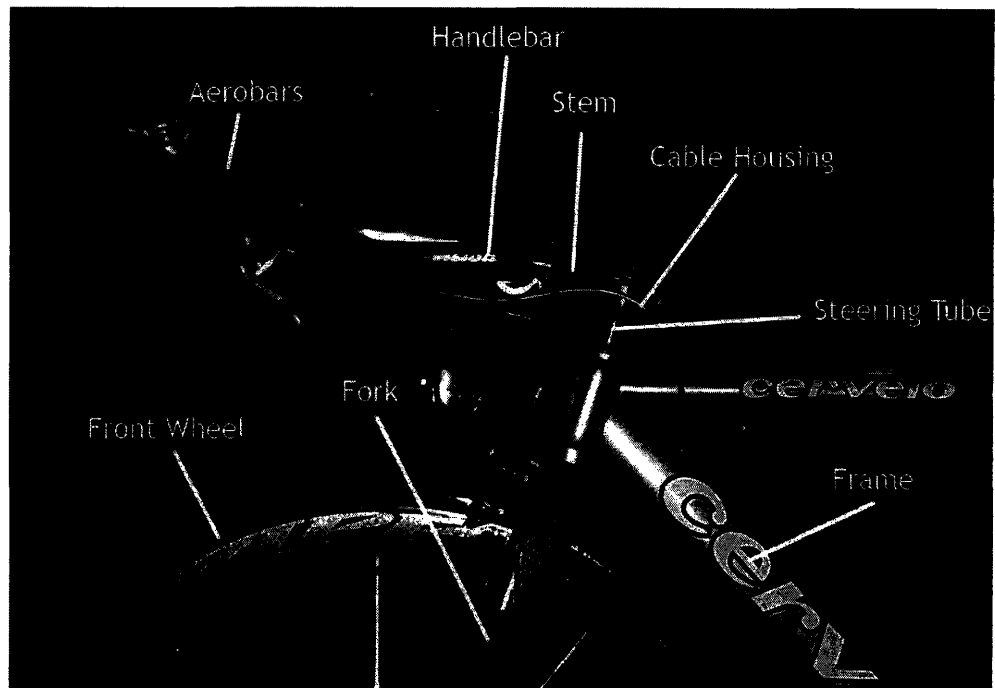


Figure 5: Labeled components on the front end of an aerodynamic bicycle.

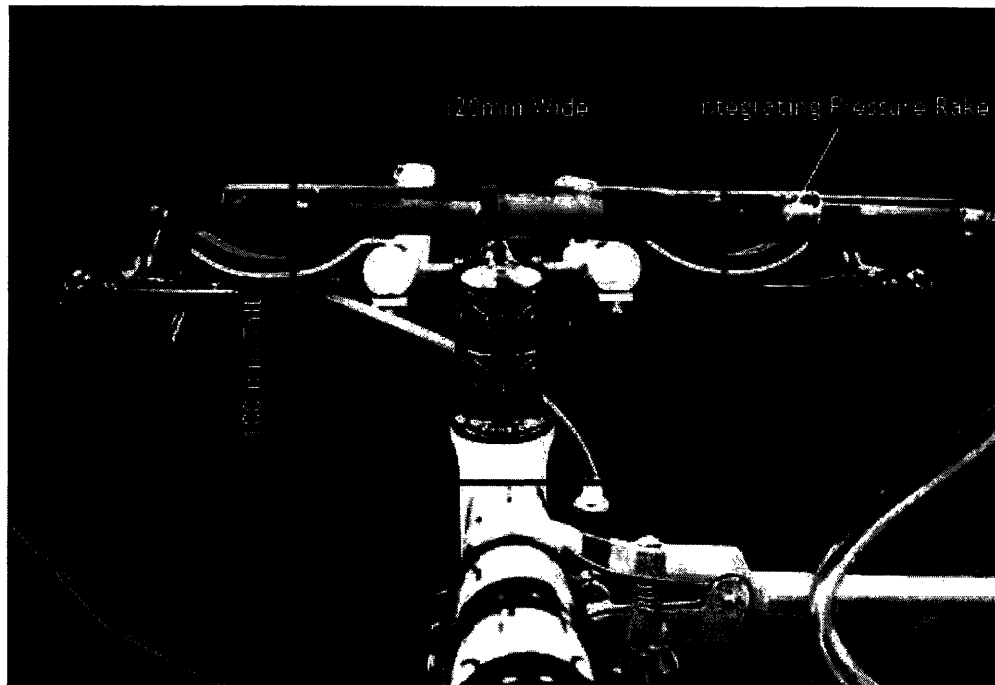


Figure 6: Area of interest for pressure measurements; behind the steering tube, handlebars, and stem.

2.1 Understanding Pressure Around a Body

The pressure drag of a blunt body can be characterized as the momentum loss of a mass of air flowing over the body. This force can be measured directly by coupling the body to a fixed load cell or by measuring the dynamic pressures upstream and downstream of the body, as is done here.

Analytically, this can be derived as follows⁴:

As depicted in *Figure 7*, assume an infinitely long channel (going into and coming out of the page) is subjected to a viscous flow. The dotted line from letters *a* through *g* denotes the control volume in *Figure 7*.

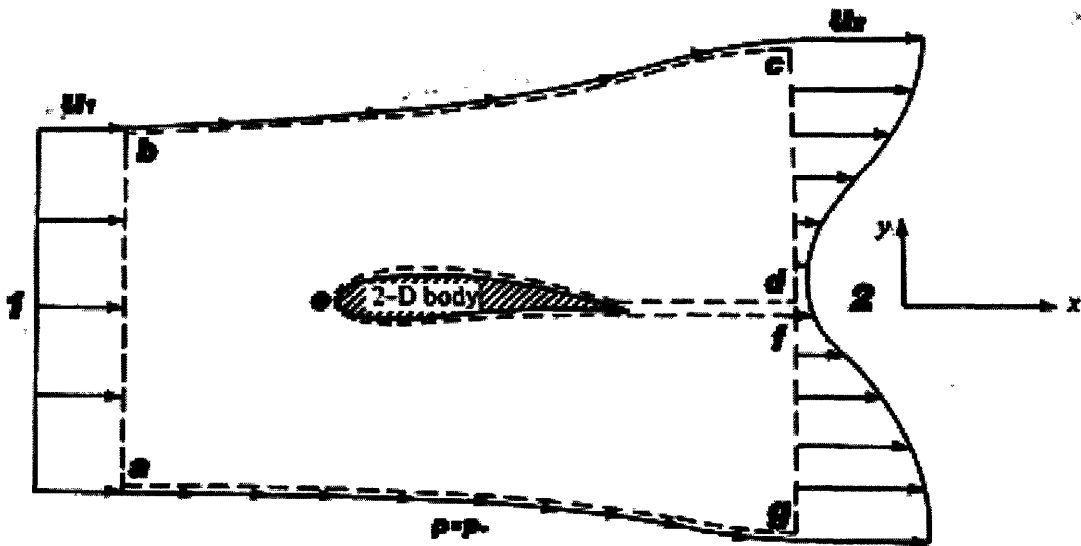


Figure 7: Diagram of fluid momentum loss downstream of a bluff body. The control volume is represented by the dotted line running from *a* to *g*.

Because boundaries *bc* and *ag* follow streamlines there is no mass flow out of the top or bottom of the control volume. Mass flows in across boundary 1 (*ab*) and out through boundary 2 (*cg*). Additionally, it should be assumed that boundary 2 is far enough downstream that the linear streamlines are parallel (thus P_{static} is equal for all heights in *y*).

Representing this mathematically, by Conservation of Linear Momentum, we have

$$\frac{dF}{dt} = D' = \dot{m}_1 u_1 - \dot{m}_2 u_2. \quad (1)$$

where D' is the drag force per unit out of the page, \dot{m}_1 and \dot{m}_2 are the mass flow rates through boundaries 1 and 2, and u_1 and u_2 are the flow velocities upstream and downstream of the body, respectively.

Additionally, since mass is conserved in the control volume, the mass flow into boundary 1 is equal to the mass flow out of boundary 2, or

$$\dot{m}_1 - \dot{m}_2 = \int_a^b \rho \cdot u_1(y) dy - \int_g^c \rho \cdot u_2(y) dy = 0 \quad (2)$$

$$\dot{m}_1 = \dot{m}_2 \quad (3)$$

Combining *Equations 1* and *3* gives us

$$D' = \rho \int u_1(u_1 - u_2) dy. \quad (4)$$

Equation 4 relates the per unit drag to the upstream and downstream velocities. Though this is the desired theoretical result, our instruments require relating velocities to dynamic pressures. First, from *Equation 4*, let

$$\Delta u = u_1 - u_2, \quad (5)$$

for use in the rest of the derivation. Then dynamic pressure, q , is related to velocity by

$$q = P_{total} - P_{static} = \frac{1}{2} \rho U^2. \quad (6)$$

Furthermore, we are measuring the difference between upstream and downstream dynamic pressures, where Δq is

$$\Delta q = q_1 - q_2 = \frac{1}{2} \rho \int_g^c (u_1^2 - u_2^2) dy. \quad (7)$$

Substituting *equation 5* into *equation 7* gives us

$$q_1 - q_2 = \frac{1}{2} \rho \int \left(u_1^2 - (u_1 - \Delta u)^2 \right) dy, \quad (8)$$

and simplifying *equation 8* results in

$$q_1 - q_2 = \rho \int u_1(u_1 - u_2) dy - \frac{\rho}{2} \int u_1 - u_2 dy, \quad (9)$$

This can also be represented as

$$\Delta q = D' - \varepsilon', \quad (10)$$

where D' is the drag force per unit height and ε' is a biased error per unit height. For $u_1 \approx u_2$ or small Δu , ε' is very small. Since the purpose of this experiment was just to evaluate the feasibility of this region for a trailing edge fairing, exact drag values are not needed and Δq can be thought to be roughly equal to D' .

Δq , as noted in *Equation 7*, is the measured difference between the measured upstream flow dynamic pressure and downstream dynamic pressures.

2.2 Measuring Pressure Around a Body

Upstream pressures were measured with a pitot tube in free stream flow. Downstream pressures were measured with a 20-port (120 mm) integrating pressure rake positioned in the area of interest. (The rake is a one-dimensional array of tubes feeding into a common tube, which sums the pressures in one dimension and outputs a single pressure.) Static pressure for the entire experiment was measured with the static port on the pitot tube. The pitot tube and integrating rake were connected to separate ports on an Auto Tran 700D 24VDC pressure transducer. Voltages from the pressure transducer were displayed on a Keithley 179-20A TRMS Multimeter. The pressure measurement system is shown in *Figure 8*.

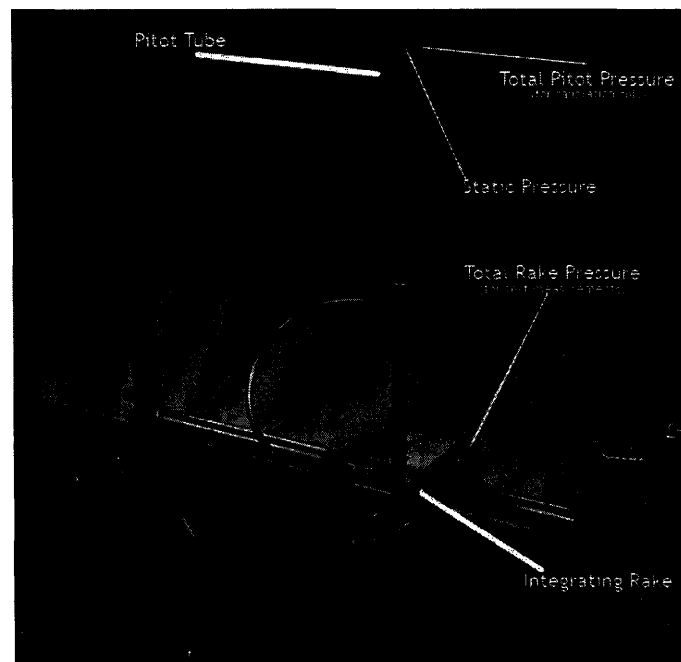


Figure 8: Pressure measurement apparatus mounted to the test bike. Dynamic pressure, q , was measured as total rake pressure minus static pressure.

The rake was placed 90 mm behind the steering tube to be adequately downstream of the flow disturbance (greater than three times the diameter of the steerer tube). Dynamic pressures were recorded at 10mm vertical increments starting at 12mm above the top tube and going up to 102mm.

Each port of the rake represented the pressure for a small rectangular section 6mm by 10mm, and thus, the resulting total test area was 100mm by 120mm (0.012m²). The wind tunnel speed was set to roughly 13.4 m/s (30 mph) for all of the tests. Due to limited time in the wind tunnel, measurements were only taken once at each point.

The results from this test are summarized in *Table 1* and *Figure 9*.

Table 1: Measured dynamic pressures relative to test height above top tube.

$u_1 = 13.5 \text{ m/s ; } n=1$										
Height Above Top Tube (mm)	12	22	32	42	52	62	72	82	92	102
q (Pa)	31.6	45.6	61.1	67.9	60.6	54.4	46.9	48.6	47.3	51.8

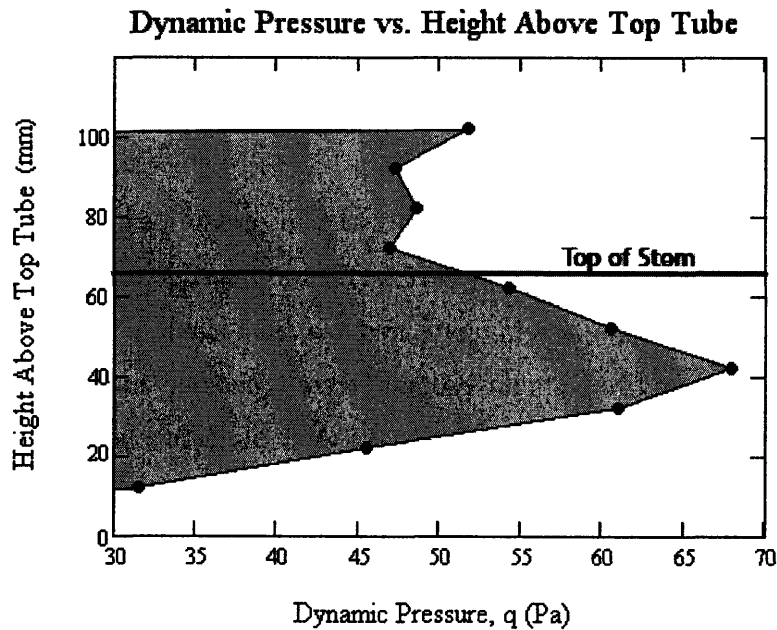


Figure 9: Vertical pressure distribution behind a typical bike steering tube. The blue line represents the top of the stem/steerer. The yellow shaded area is the pressure drag from the upstream components.

Figure 10 relates the pressure distribution in *Figure 9* to the area of interest on the bike.



Figure 10: Reference test location and relative pressure distribution.

This pressure gradient shows the lowest pressures on the bottom half of the steering tube (below the stem). Here, the flow needs to go directly around the cylindrical steering tube or over the top of the bars to resume free stream flow. Thus, the lowest pressures are within 35mm of the top tube.

Above here (35mm-60mm), the increase in pressure directly behind the stem shows that the bolts and additional material on the trailing edge (due to the stem) actually decrease the wake size behind them (compared to a raw cylinder).

Above the stem (from 60mm-100mm), there is another small low-pressure region. This low-pressure zone is most likely due to the wake of the handle bar.

To determine drag, the measured rake dynamic pressures were multiplied by 0.0012m^2 (0.12m by 0.01m; the area each rake pressure measurement represented). Then, the resulting forces were summed up to find the total drag due to these components.

2.3 Results and Discussion

The test resulted in a calculated drag of 0.619 N (minus some ϵ , as suggest in *equation 10*) for the 120mm by 100mm area behind the steering tube. Given that the biased error in the test could not be empirically measured, these values may be 10-20% higher than the actual induced pressure drag. Even taking into account a 20% error, comparing this to the overall drag of the entire bike directly measured using a load cell (data from a separate test on November 30, 2006; $n=1$, $F_{\text{drag}}=5.29$ N), the drag of this small volume accounts for roughly 10% of the overall drag due to the bike. Compared to the entire bike/rider system drag (data from a test on May 23, 2006; $n=1$, $F_{\text{drag}}=21.4$ N), the drag of this volume accounts for roughly 2% of the overall drag of the system.

The data suggests that a large amount of the bicycle drag comes from this small section of the bicycle frame. A comparison of drag due to this volume and the drag of a front wheel shows the true significance of this data. Past tests at the Wright Brothers Wind Tunnel on wheels (0 degree yaw, wind speed = 13.41 m/s; $n=1$) have shown drag deltas (between best and worst front wheels) of 0.71 N. As the drag comparisons are similar in magnitude, the data suggests that improving the drag associated is as important as work on wheel aerodynamics.

Future pressure analysis of the test region should include wind tunnel tests with the bike yawed at with respect to the free stream flow. Any future tests should also be done with the rake different distances from the head tube to validate the experiment. Several data sets should be taken to determine the statistical significance of the data. Unfortunately, the wind tunnel schedule did not warrant more than thirty minutes for this test and thus only one data set was taken.

2.4 Conclusion

From the results, the region of interest seems to be a very viable region for a trailing edge fairing. The induced pressure drag of this region will vary from bike to bike and the amount of improvement from a fairing will vary as well. No matter what bicycle type though, the fairing should mate as well with the trailing edge of the steerer to provide a smooth transition for the flow from the steering tube to the reservoir. More specific design parameters are discussed in the *Product Design* section.

3.0 IDENTIFYING PRODUCT OPPORTUNITY

3.1 Product Mission Statement

Aerodynamic performance alone will not make this a successful consumer product. Despite the potential performance advantages resulting from placing a fluid reservoir on the top tube of the bike, there are several more explicit needs that the market consumer requires. In developing that list of needs, a general product mission statement should first be stated to clarify purpose and help to maintain a focused direction during the product development process⁵.

Mission Statement: Aerodynamic Water Bottle/Hydration Unit

Product Description:

- A bicycle-mounted reservoir for the carrying and hands-free delivery of liquids to a cyclist while riding

Key Business Goals:

- Simple design with fewer than 10 parts
- Landed cost of goods <\$8 with packaging

Primary Market

- High-end, performance driven male and female triathletes and cyclists in the United States; athletes racing sprint distance (750 m swim, 20 km bike, 5 km run) up to half-iron distance triathlon (2 km swim, 92 km bike, 21 km run)

Secondary Markets

- Entry level triathletes; casual amateur triathletes
- Recreational cyclists

Baseline Product Assumptions

- Removeably mounted to the bicycle toptube
 - Mounts to at least 85% of road bicycles
 - Holds at least 620 mL (21 oz.; same amount as a traditional water bottle)
-

Armed with a basic mission statement, a qualification of the primary and secondary needs of the market consumers was needed to effectively benchmark current products on the market and eventually develop concrete product specifications for the proposed design.

3.2 Customer Needs

Typically, during the product design process, consumer needs are revealed through a consumer survey, focus group, or several individual interviews with market consumers. Though many athletes were interviewed in the process of this product design, no formal survey or discussions were conducted. Rather the consumer needs were identified through casual discussions with triathletes and cyclists. As the author is also a competitive triathlete and cyclist, he identified personal needs that were consistent with those of interviewed athletes. These needs, along with comparison to competitive products, developed into a set of design specifications as noted in the *Product Design* section. The customer needs are summarized in *Table 2*.

Table 2: Customer needs prioritized based upon importance to the athlete. 5 is very important, 1 preferred but not essential

Number		Need	Importance
1	The bottle	carries enough liquid for an hour long race.	5
2	The bottle	remains sealed and does not splash the rider when riding.	5
3	The bottle	can deliver fluid without the use of hands.	5
4	The bottle	mounts to a bike simply and easily.	5
5	The bottle	mounts rigidly to the bike and stays put.	5
6	The bottle	is USA Triathlon legal*	5
7	The bottle	is UCI legal*	4
8	The bottle	works on almost all road bicycles.	4
9	The bottle	can be replaced or refilled easily while riding.	4
10	The bottle	does not interfere when rider mounts the bicycle.	4
11	The bottle	does not interfere with normal riding style.	4
12	The bottle	is safe in a crash.	4
13	The bottle	can be cleaned by hand or in a dishwasher.	4
14	The bottle	is more aerodynamic than a normal water bottle.	4
15	The bottle	makes the athlete feel fast.	3
16	The bottle	does not retain tastes or odors after washing.	3
17	The bottle	does not scratch the frame when mounting or mounted.	3
18	The bottle	is affordable for an amateur enthusiast.	3
19	The bottle	has good clarity and scratch resistance.	3
20	The bottle	shows the available amount of fluid left in the reservoir.	2
21	The bottle	is lightweight.	2
22	The bottle	is recyclable.	1
23	The bottle	accepts normal ice cubes.	1

**Legality refers to equipment regulations for each of the major sport governing bodies: USA Triathlon sets the equipment guidelines for triathlon in the United States and the Union Cycliste Internationale (UCI) sets the road cycling rules for most of the world.*

3.3 Derived Product Metrics

Table 2 gives a good indication of what is important to the market consumer, but needs alone did not give the proper direction for developing product appearance or function. Metrics and specifications derived from the consumer needs helped to quantify deliverable product goals by giving measurable expectations. Table 3 gives a list of deliverable metrics based upon the consumer needs in Table 2.

Table 3: Metrics for Product Specifications

Metric Number	Need Numbers	Metric	Importance	Units
1	1	Capacity	5	mL
2	3	Hands-free delivery of fluid	5	Binary
3	4	Time to mount on a bike	5	Seconds
4	6	USA Triathlon Legal	5	Binary
5	5	Torsional load for product slippage	5	N ·mm
6	10, 11	Geometry of reservoir (w x l x h)	4	mm
7	9	Time to refill reservoir while bike	4	Seconds
8	9	Time to remove from bike	4	Seconds
9	7	UCI Legal	4	Binary
10	14, 15	Head-on aerodynamic drag change**	4	N
11	8	Bicycle compatibility	4	List, %
12	9,23, 2	Geometry of fill opening	4	mm
13	12	Height of drop without breaking	4	mm
14	13, 16	Dishwasher safe	4	Binary
15	18	Price	3	\$ USD
16	17	Hardness of interface with frame	3	Hardness
17	19, 20	Clarity of translucence	3	Subjective
18	21	Total mass	2	g
19	22	Recyclability	1	Binary

**** aerodynamic drag delta for head-on test at 30 mph versus a bike frame with one mounted 620 mL tradition bottle and cage**

3.4 Product Benchmarking

The same products have filled the aero water bottle niche for the past decade. Most of these systems have remained virtually unchanged during this period and most offer only mediocre performance. In addition to their constant spilling, clunkiness, and challenging usability, few have actually been designed with any aerodynamic knowledge. Often they are designed to just look aerodynamic. However, there are a few systems that address many of the riders' needs well and those systems have price points between \$20 and \$100. Two competitive products are shown mounted on bicycles in *Figures 11 and 12*.



Figure 11: The NeverReach system (\$99) mounts behind the seat and offers easy on-the-fly refill capability and a huge 1890 mL (64 oz.) container.



Figure 12: The Profile Aero Drink system (\$27) mounts in between the aerobars and can hold up to 830 mL of water. Its fill-on-the-fly splashguard, made of a yellow mesh plastic, is notorious for bouncing out of the container during races.

Hydration systems are traditionally categorized by where they are mounted on the bike – behind the seat (*Figure 11*), between the aerobars (*Figure 12*) and on the traditional water bottle mounts inside the front triangle (*Figure 4*). Additionally, some triathletes even use flexible bladder systems that they wear like a backpack or stuff in the back of their jerseys, but these are bulky and require time in the triathlon transitions to put on and take off.

There are currently no hydration systems available on the market that mount to the top tube of a bicycle as suggested in this paper. *Table 4* includes a list of currently available systems, their fluid capacity, and the current US pricing. The prices are noted as the cost of the complete system including mounting hardware and bottles.

Table 4: Several current hydration products and their price points, styles, and capacity.

Product	MSRP (USD)	Mount Location	Capacity (mL)
Profile Design AeroDrink	\$26.90 (w/ mount)	Aerobars	830
Podium Quest Revolution	\$44.95	Aerobars	1480
X Lab Saddlewing	\$65.95 (2 cages)	Saddle (Round Bottles)	1240
NeverReach System	\$99.95	Saddle	1890
Bontrager Speed Bottle	\$59.95 (w/ cage)	Frame Bosses	590
Specialized Big Mouth and Rib Cage Pro	\$19.98 (w/ cage)	Frame Bosses (Round Bottle)	620

Table 5 shows a competitive benchmarking chart for the perceived satisfaction of the athlete’s needs stated in *Table 2*. One “dot” means totally unsatisfactory, three dots means satisfactory, and five dots represents a complete solution for the need.

Table 5: Perceived need satisfaction for competitive products.

Number	Need	Imp.	Profile Design	Podium Quest	X Lab	NeverReach	Arundel	Specialized
1	Carries enough liquid for an hour long race	5	•••••	••••••	••••••	••••••	••••	••••
2	Remains sealed and does not splash the rider when riding	5	•	••	••••••	••••••	••••••	••••••
3	Can deliver fluid without the use of hand	5	••••••	•••••	•	•••••	•	•
4	Mounts to a bike simply and easily	5	••••	••	•	•	•••••	••••••
5	Mounts rigidly to the bike and stays put	5	••	••••	••••	••••	••••••	••••••
6	Is USA Triathlon legal	5	yes	yes	yes	yes	yes	yes
7	Is UCI legal	4	no	no	no	no	yes	yes
8	Works on almost all road bicycles	4	••	••	••••	•••••	•••••	••••••
9	Can be replaced or refilled easily while riding	4	•••••	•••••	••	••••••	•	••••
10	Does not interfere when rider mounts the bicycle	4	••••••	•••••	•	•	••••••	••••••
11	Does not interfere with normal riding style	4	••••••	•••••	••••••	•••••	••••••	••••••
12	Is safe in a crash	4	••	••••	••••	••	•••••	••••••
13	Can be cleaned by hand or in a dishwasher	4	yes	yes	yes	yes	yes	yes
14	Is more aerodynamic than a normal water bottle*	4	••••••	••••••	••	••	•••••	••••
15	Makes the athlete feel fast	3	••	••	•	•	•••••	•
16	Does not retain tastes or odors after washing	3	••••	••	••••	••••	••••	••••
17	Does not scratch the frame when mounting or mounted	3	•••••	•••••	••	••	••••••	••••••

Number	Need	Imp.	Profile Design	Podium Quest	X Lab	NeverReach	Arundel	Specialized
18	Is affordable for an amateur enthusiast	3	•••••	•••	•••	•	••	•••••
19	Has good clarity and scratch resistance	3	••	••	•	•	•	•
20	Shows the available amount of fluid left in the reservoir	2	•••	••	•	••	••	•
21	Is lightweight.	2	•••	••	••	•	••••	••••
22	Is recyclable	1	••••	••••	••••	••••	••••	••••
23	Accepts normal ice cubes	1	yes	yes	yes	yes	no	yes

**test results from unpublished tests at the MIT Wright Brothers Wind Tunnel; February 2007*

As clearly shown in *Table 5*, the style of bottle and mounting location has a primary impact on the usability of the product. Generally, aerobar mounted systems (Profile Design and Podium Quest) offer the best access to fluids while riding but their poor “splash-guards” cause them to soak the athlete with water or sports drink while riding. Both rear mounted bottle racks and frame-mounted cages hold their reservoirs rigidly, but make taking a drink difficult and time consuming. Though frame mounted bottles do not splash or leak, they do not have the necessary capacity for long races and thus need to be replaced. Aerodynamic shaped water bottles, such as the Bontrager Speed Bottle, have custom bottles and cages so replacement can only be made with the correct reservoir; normal bottles cannot be retained in their cages. *Figure 13* shows a picture of the Bontrager bottle and carbon-fiber cage.



Figure 13: Bontrager Speed Bottle, aerodynamic water bottle and cage. Though the bottle mounts rigidly to the frame, its small capacity and custom cage make it unappealing for longer races.

As most or all of these bottles are made out of some type of polyethylene, (HDPE for rigid bottles, LDPE for squeezable bottles), they are opaque and difficult to see through. Beyond this being aesthetically unappealing versus a more transparent material, it also makes it difficult to gage the amount of available liquid while riding.

Additionally, only aerodynamic bottles (Bontrager) have an appeal that makes the user *feel* fast. None of the other products offer design styling with swept lines or skinny profiles. None of the products are marketed with aerodynamic comparisons to other products. Without this data, few consumers would realize the huge potential performance of hydration products (as suggested in *Section 2*). For the high end user, performance perception is crucial, as many racers will purchase products due entirely to how it makes them feel.

Using these unmet needs as refined design goals, a new product in this category needs to:

- Be refillable on-the-fly with traditional handouts (round water bottle)
 - Not splash the rider
- Offer totally hands free use
- Allow the athlete to view fluid capacity while riding
- Make the athlete faster or at least feel faster

With these goals in mind, sketches and models were made to realize the form and functions of a new product in this category.

4.0 PRODUCT DESIGN

When developing specific designs, it was crucial to come up with a new style of product in addition to one that functioned well. A new bottle that mounted between the aerobars would be considered a copy of the Profile Design bottle even if it offered better usability or performance benefit. Due to the results of the wind tunnel pressure test and a goal of creating a unique product, brainstorming began for a top tube mounted water bottle.

To answer the unmet needs listed in *Section 3.3*, the design was focused around four key areas: fill design, fluid delivery, reservoir shape, and reservoir mounting.

4.1 Concept Sketches and Models

The first proposed design would include less than ten parts and would mount to the top tube using a few Velcro or rubber straps wrapped around the bottle to the top tube and the steerer. A flexible straw would extend out of the top of the bottle, over the stem, and could be positioned to allow the athlete hands-free access. The cap would allow the athlete to drain a bottle into the container without the liquid splashing up while riding.

Figures 14 and 15 show sketches of the original bottle concept as well as the functionality of the cap design.

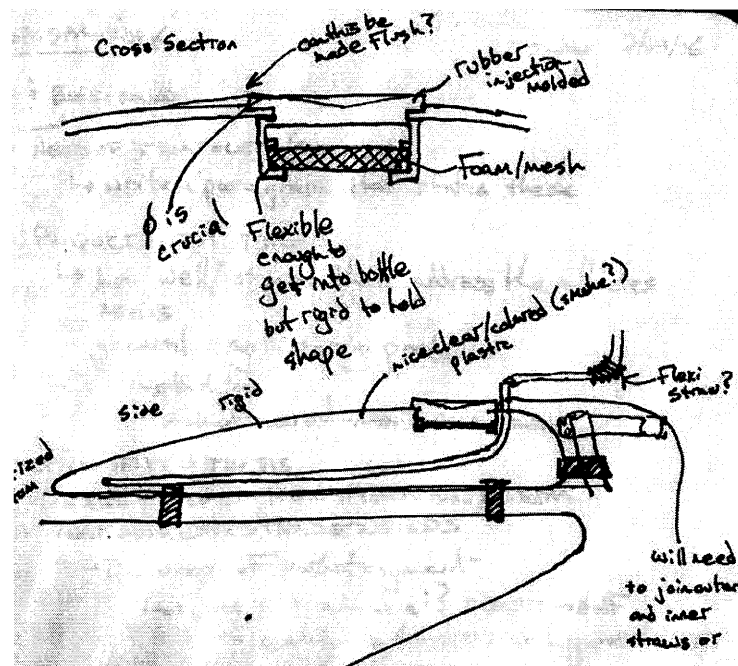


Figure 14: Concept sketch of the cap, straw, and securement system.

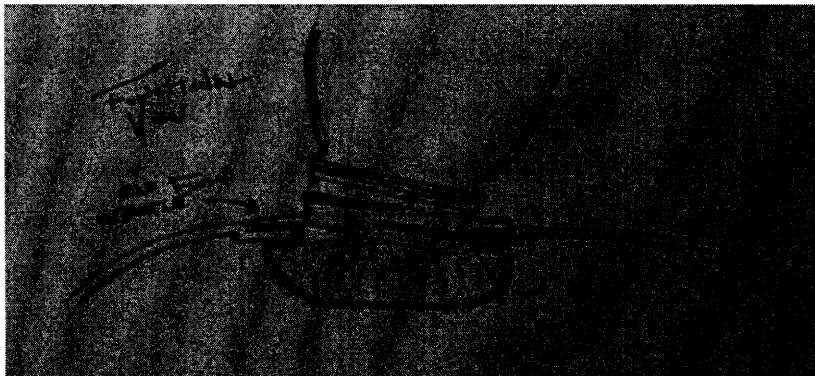


Figure 15: Functional sketch of a concept splash guard/cap for a water bottle. Early designs suggested an opening large enough to pour wide mouth sports drink bottles into the reservoir.

The base of the bottle would be contoured to slightly wrap around the top tube. Due to the variation in top tube designs today, this contour would be fairly shallow and lined with a neoprene or rubber to securely hold the tube. This purpose of this feature would also be to avoid scratching the top tube of the bike.

These sketches were very useful in understanding a realization of the product requirements. However, understanding the geometry of the product was crucial as well. Thus, several mockups of the different parts were made. *Figure 16* shows an early high-density polyurethane foam model that was cut and sanded to a conceived shape. This model ended up being the first three-dimensional model created and helped to understand product interference with cyclists' pedal stroke.

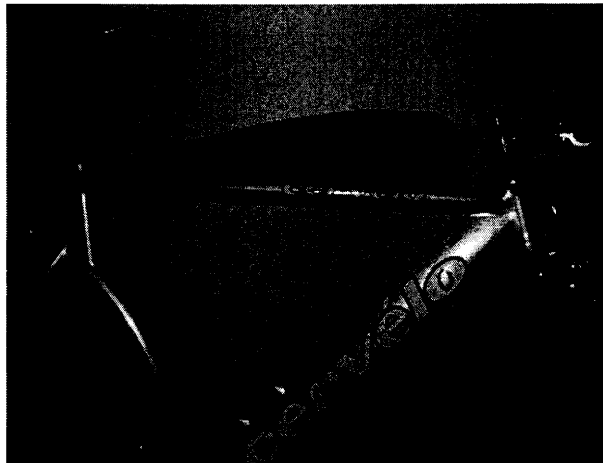


Figure 16: HD polyurethane foam model used to understand the three-dimensional geometry of the product.

Even though aerodynamics were crucial for this design, it was more important that a rider could pedal comfortably with the reservoir between his or her knees. This requirement quickly set the maximum height and length of the bottle. Additionally, the varying lengths and angles of bicycle top tubes made it crucial to pick a length that could fit even the smallest bikes. The creation of this model set baseline geometry of the reservoir to 400mm long by 70mm wide by 80mm tall. Any bottle made for this region of a bicycle would have to be that size or smaller.

4.2 Product Specifications

Working with simple plastic and foam mockups, values for the product metrics discussed in *Table 3* were created. Thus, working specifications were set for the project. These are shown in *Table 6*.

Table 6: Working specifications for a top tube mounted aerodynamic water bottle.

Metric No.	Need Nos.	Metric	Imp.	Marginal Value	Ideal Value	Units
1	1	Capacity	5	620	1200	mL
2	3	Hands-free delivery of fluid	5	Yes	Yes	Binary
3	4	Time to mount on a bike	5	-	<180	Seconds
4	5	USA Triathlon Legal	5	Yes	Yes	Binary
5	5	Torsional load for product slippage	5	650	1500+	N ·mm
6	8	Time to refill reservoir while bike	4	-	10	Seconds
7	10, 11	Geometry of reservoir (w, l, h)	4	50, 250, 50	70, 450, 85	mm
8	8	Time to remove from bike	4	-	<30	Seconds
9	6	UCI Legal	4	No	Yes	Binary
10	13, 14	Head-on aerodynamic drag change**	4	-2	<1	N
11	7	Bicycle compatibility	4	60%	100%	List, %
12	8,22, 2	Geometry of fill opening	4	Ø23	Ø55	mm
13	11	Height of drop without breaking	4	2	6	m
14	12	Dishwasher safe	4	No	Yes	Binary
15	17	Price	3	20	100	\$ USD
16	16	Hardness of interface with frame	3	30	60	Hardness
17	18, 19	Clarity of translucence	3	Semi-transparent	clear	Subjective
18	20	Total mass	2	150	<500	g
19	21	Recyclability	1	No	Yes	Binary

** aerodynamic drag delta for head-on test at 30 mph versus a bike frame with one mounted 620 mL tradition bottle and cage

4.3 Development of a CAD Model

Given the sketches, mockups, and specifications, a computer aided drawing (CAD) model was created to build a working model that could be edited very easily, interfaced with several different computer drawn parts, and eventually be rapid prototyped directly from the files. SolidWorks 2006 with surfacing was used for the development of this model. This process begins with several outlines and boundaries in each plane. One such side boundary is shown in *Figure 17*.

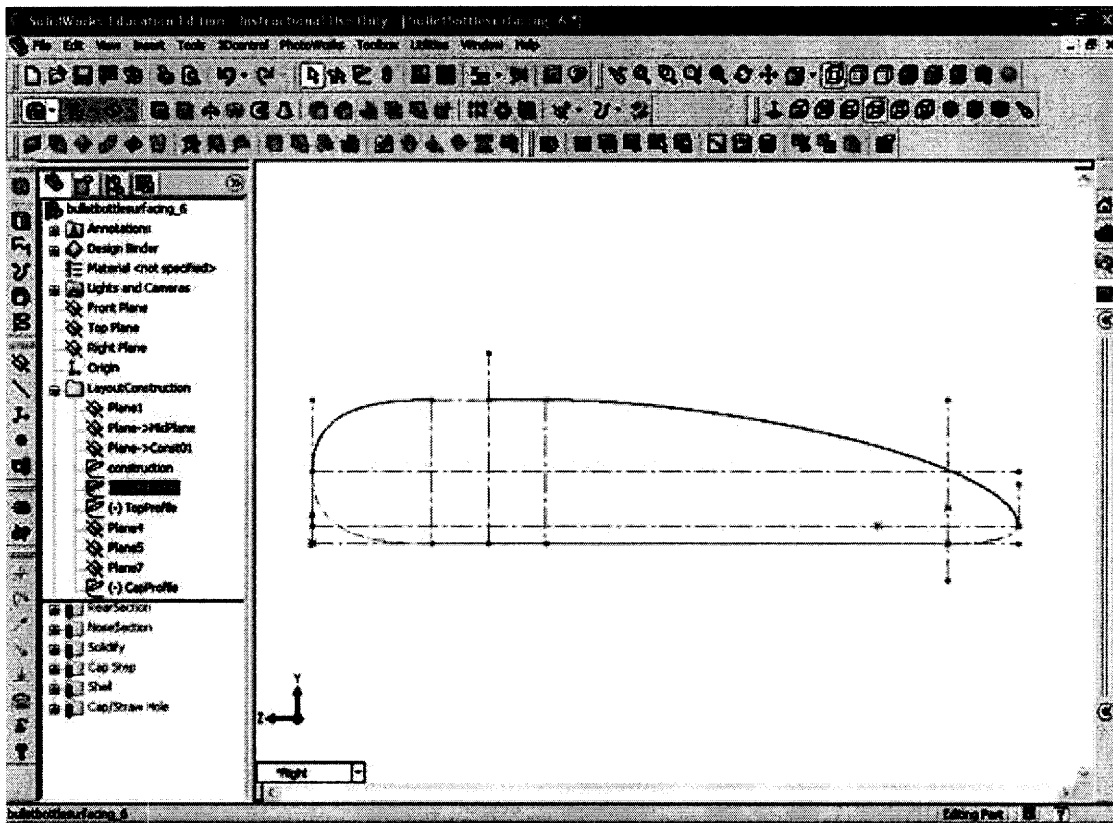


Figure 17: SolidWorks 2006 view of the side layout of a surfacing model of the reservoir.

Constructing several views of the desired result allows for the development of complex shapes as shown in *Figure 18*. Note that though the surfaces look to be seamless, they are actually made up of four separate sections. *Figure 19* shows the bottle modeled onto a bicycle.

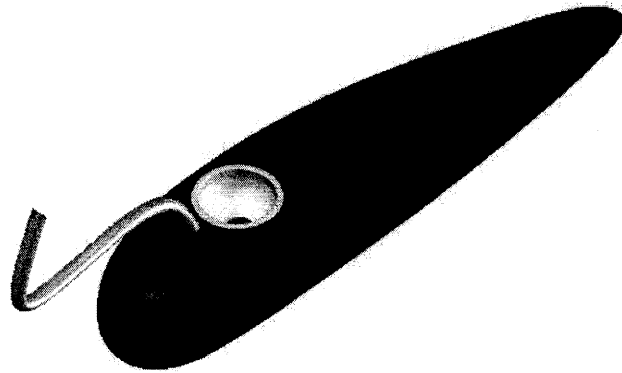


Figure 18: Isometric view of initial CAD assembly



Figure 19: CAD model mated onto a bicycle frame.

Though the bottle design changed in shape and geometry, after the first CAD model was created, only small modifications were made to the design. Generally, the maximum width, which was originally set to allow turning over a full wide-mouth sports drink bottle into the fill-cap, decreased to accommodate narrower pedal strokes. Additionally, the underside of the reservoir was adjusted to fit a variety of tube shapes.

The biggest difficulties came in deciding how to mount the bottle to the tube of the bike frame. Bicycle frames generally offer two sets of water bottle cage bosses on the seattube and downtube. Since this bottle was to mount above the top tube, some type of manufacturable solution would be required. After experimenting with several different attachment styles, it was decided that Velcro should wrap around the entire bottle and tube. By adhering the loop part of the Velcro to the base of the bike's top tube and indentations on the side of the bottle, a wrap of hook Velcro would provide a compressional and torsional load on the bottle so it would not move from the top of the top tube. Additionally, a textured silicon rubber was added to the base to avoid scratching the bike, give extra torsional support to the bottle, and allow for compression when tightening the Velcro straps. The resulting bottle is displayed as a top view in *Figure 20*.



Figure 20: Top view of the bottle Velcro-ed to a tube.

The other crucial part in this product design was the cap/valve. One of the major four goals of this project was to devise a way to fill the bottle while riding without bumps on the road causing liquid to splash out of the container. Early mockups of this were hard plastic concave shells as shown in *Figure 21*.

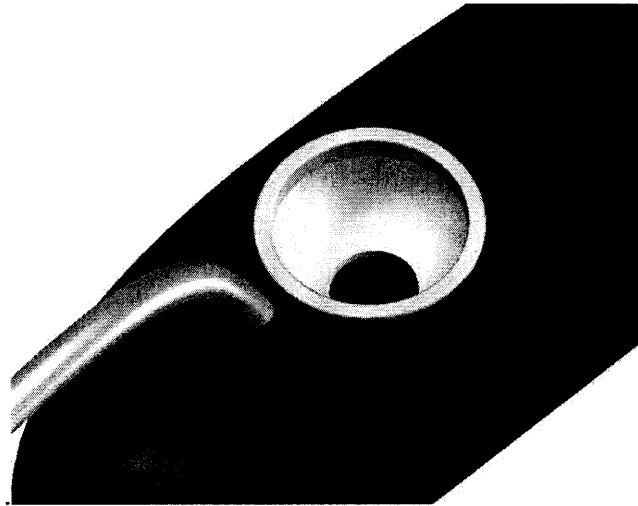


Figure 21: Rigid cap design that allowed for fill-on-the-fly access. The large center hole still allowed for fluid to splash back up and the design was shelved.

The round piece shown above was concave above and allowed for a bottle with up to 44 mm outer diameter to be poured into the reservoir. However, even with the concave shape, testing with prototype showed that large bumps would cause fluid to splash out of the container. The design was shelved and a new concept was explored.

By the recommendation of a professor in Mechanical Engineering, one-way check valves were explored. The concept was to design a flexible check valve that would allow an athlete who was handed a traditional water bottle to squeeze the fluid in through the valve and then have it close if fluid splashed back up. Developing this idea outside of CAD was challenging, so a model was created around the parameters of the reservoir and existing round water bottle caps to allow for easy filling of the bottle. The resulting valve design evolved as the reservoir design changed. *Figures 22 and 23* show isometric views of the bottle and valve assembly and the valve only, respectively.

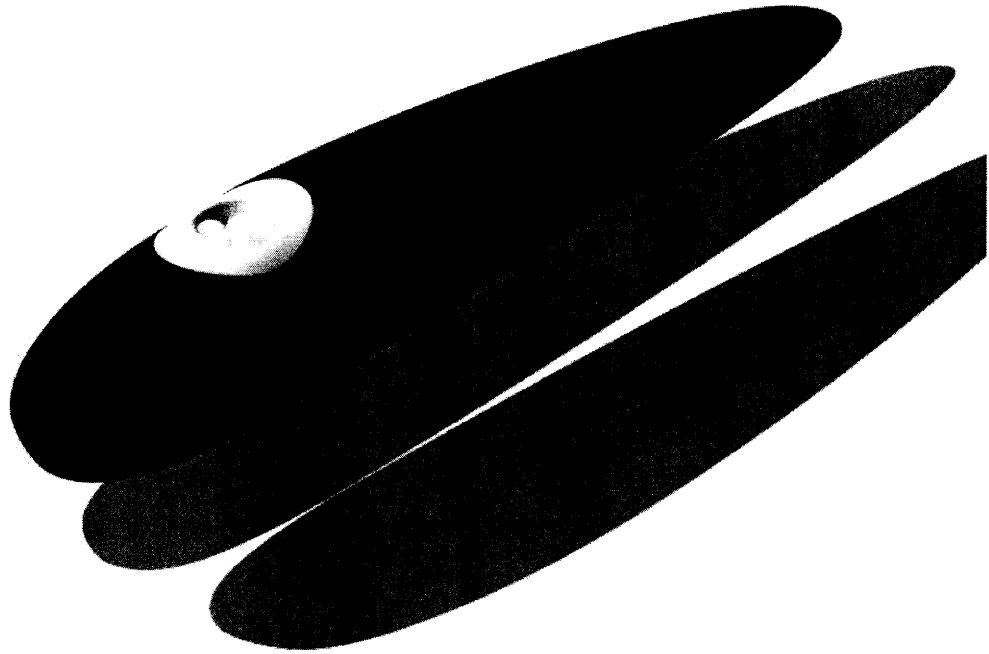


Figure 22: Final bottle shape and silicon valve for fill-on-the-fly capabilities

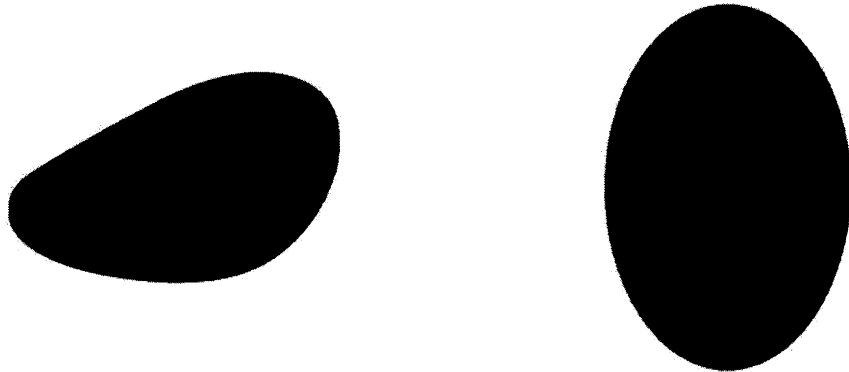


Figure 23: Silicon valve for aerodynamic reservoir. The isometric view on the left shows an opening for a traditional water bottle to squeeze into. The flaps of the valve then open and allow the fluid to pass through. A top view is shown on the right.

The additional parts of the bottle were specified to be off the shelf components. The Velcro, silicon rubber (for base of the bottle), and PVC tygon tubing used as a straw are all available components. Future design work would include further working of the mounting and securement of the straw, as well as the reservoir itself.

5.0 CONCLUSION AND FUTURE WORK

From the wind tunnel tests, product benchmarking, and initial response from showing the product renderings to triathletes, this product design seems to be very viable in today's triathlon and cycling markets. There are still major design challenges that exist in finalizing the design, but overall, the simplicity of the design makes it cheap to manufacture.

To verify the product viability going forward, it would be necessary to develop several prototypes that athletes could try. Getting first hand feedback from athletes would be the best way to see how the product might be used and understand the faults of the current design.

To verify product performance, comparative wind tunnel testing with the available aerodynamic hydration products should be completed. Several products and prototypes should be tested in parallel with several different athletes and bikes to understand the aerodynamic effects of small and large riders on several different types of bikes. Both road and triathlon style bikes should be used for the study. Additionally, cross wind testing would give an even great understanding of the performance of these products in several different real world cases. As there have been very few studies in this area in the past, the data would be very valuable for the industry and might begin to show how much hydration products influence performance.

6.0 ACKNOWLEDGEMENTS

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Thanks are also due to Professor Alex Slocum for his constant reminders of simplicity in engineering and his recommendation of using the tri-cuspid valve, ubiquitous in nature, and soon to be in aerodynamic water bottles.

Finally, the author would like to acknowledge the countless hours of mentoring of Dr. Kim Blair has given him over the past four years. His direction, assistance, and constant belief in the author's abilities are what inspired this project and made the developments possible.

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All MSRP data was found on manufacturers websites.