

Defining, Measuring and Improving
AERODYNAMIC TESTING
IN THE BICYCLE INDUSTRY

PREPARED BY EASTON CYCLING





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Introduction

If you were to attend any triathlon, Grand Tour or simple Sunday-morning group ride, chances are you'd notice an abundance of overtly aerodynamic bicycle frames, apparel and components on display, which begs the question: Why?

Why have aerodynamics become a major priority for so many cyclists? Is this much ado about nothing or is there some validity behind the growing movement to get as “aero” as possible?

The short answer is, yes, aerodynamics matter. In layman's terms, aerodynamics matter “a lot”. In more practical (and scientific) terms, anywhere between 70 to 90 percent of a cyclist's effort (when not climbing a steep grade) is dedicated to plowing through the air.

Anyone—hardened pro and neophyte alike—who is interested in riding faster or further has a vested interest in improving their aerodynamics. It's that simple.

Determining which bicycles and components are truly the most aerodynamic, however, is anything but simple.

Demystifying Aerodynamics

Dozens of companies claim to produce the “most aerodynamic” bicycles and components available. And nearly all provide scientific data, which “prove” that their product is the most aerodynamic product of its kind on the market. How can they possibly all be “the most aerodynamic”?

Adding to the confusion, companies often employ different statistics and terminology to prove how well their products cheat the wind. One wheelset is the most aerodynamic at 5 degrees of yaw. Another is the fastest on the planet at 10 degrees of yaw. What does that even mean? To the average consumer, cycling aerodynamics is a subject shrouded in confusing science and no small amount of black magic.

Transparency in aerodynamic testing is of the utmost importance, which is why we will outline our own testing protocols in this paper—detailing every step of the process and explaining our methods, rationale and assumptions. We’re confident, from our years of designing and testing aerodynamic products, that we’ve created a testing methodology in the wind tunnel that most closely replicates the actual conditions riders experience in the real world. What’s more, we hope to inspire other companies to lay their own cards on the table, so to speak, so that consumers can gain a better grasp on aerodynamics.

The ultimate goal of this white paper is to demystify the subject of aerodynamics and to make the case for a more consistent and intuitive means of measuring and comparing the aerodynamics in the cycling industry.

In doing so, we’ll address:

- What exactly is aerodynamic drag?
- The impact drag has on cycling performance.
- The manner in which drag is typically measured.
- The limitations and challenges engineers face in reliably measuring drag.
- The potential of Wind Averaged Drag to simplify and improve aerodynamic testing in the cycling world.

Finally, a note regarding the tone of this paper...

In covering the subject of aerodynamics, we’ve attempted to achieve a balance between accurate scientific analysis and plain-speak. Our goal isn’t to oversimplify aerodynamics, but rather to create a discussion on aerodynamics that is accessible to as broad an audience as possible—one that includes riders, designers and bicycle-industry leaders alike.



To the average consumer, cycling aerodynamics is a subject shrouded in confusing science and no small amount of black magic.

...and it shouldn't be.

The Drag Equation

$$F_D = \frac{1}{2} \rho v^2 C_D A$$

(DRAG FORCE) = (1/2) x (AIR DENSITY) x (VELOCITY SQUARED) x (DRAG COEFFICIENT) x (REFERENCE FRONTAL AREA)

The drag coefficient "Cd" contains all the complex dependencies and is usually determined experimentally.
Choice of reference frontal area A affects the value of "Cd".

**Upwards of 70 percent
of a cyclist's effort*
is spent on pushing themselves
through the air.**

* the exact amount varies based on rider velocity

The Physics of Slow

Imagine a theoretical world in which you, the cyclist, no longer have to contend with the effects of gravity, or the deleterious effects of rolling resistance, friction and air resistance.

In this theoretical world, you'd be incredibly fast. The basic forces of nature would no longer act in concert to slow you down.

Generally speaking, it is a very good thing this is only theoretical, as pedaling down to the local coffee shop would be nightmarish in a zero-gravity environment, devoid of life-sustaining oxygen and the myriad laws of physics that keep coffee shops and bicycles safely rooted to the ground.

So, for better and for worse, we live in a world governed by physics and that, in turn, impacts every cyclist's velocity and effort on the bike. The following are forces that reduce a cyclist's velocity and force them to increase their effort to simply maintain a consistent velocity on the bike.

- Rolling resistance (between bicycle tires and the ground).
- Friction in the bicycle's bearings.
- The weight of the bicycle.
- The rider's body weight.
- The aerodynamic drag of your bicycle.
- The aerodynamic drag of the rider's body.

Weight—both of the bicycle and its rider—also plays a role in the grand scheme of things. Weight is most keenly experienced on steep climbs. The steeper the climb, the more gravity is felt by the rider, and the more weight becomes the predominant factor in determining his or her velocity.

This helps explain why the most successful climbers in professional road racing tend to be slight of build and possess excellent power-to-weight ratios. Likewise, professional teams seeking to provide their riders with the greatest mechanical advantage often outfit their racers with ultra-light wheels during stages featuring major climbs.

While weight matters, it is rarely the primary force that impacts your velocity and effort as a cyclist because the bulk of a rider's time isn't spent scaling steep grades. Unless you live in a town surrounded by hors categorie climbs, the force that has the greatest impact on your velocity and level of exertion on the bicycle is, hands down, air resistance.

On a 68-degree (Fahrenheit) day at sea level, a cubic foot of dry air tips the scales at a mere 1.25 ounces. Not a terribly impressive figure. If you stop for a moment now and pass your hand through the air, you'll find it an effortless gesture.

On a bike, however, you are traveling at much greater speeds and you, in combination with a bicycle, present a much bigger obstacle to air flow. The resistance you feel from the air is, consequently, much higher.

Thus, if you were to now get in a car, drive down the road and stick your hand out the window of the speeding vehicle, you'd feel a great deal of resistance. Neither the gesture nor the atmosphere has changed, but your velocity and resulting aerodynamic drag have. Drag is proportional to your effective wind velocity squared as illustrated in the equation on the facing page.

Upwards of 70 percent of a cyclist's effort (the exact amount varies based on rider velocity) is spent on pushing themselves through the air. What's more, once a rider attains a velocity in excess of 15 miles per hour, the amount of effort required to attain each additional mile per hour increases exponentially. The force at play here is aerodynamic drag

¹Kyle, C.R. and Burke, E.R. (1984) Improving the racing bicycle, Mechanical Engineering.

Friction Drag, Pressure Drag... Aerodynamic Drag is, Well, a Drag

When an object moves it displaces air—forcing air to move around and behind it. The friction of the air passing over the surface of the object (skin friction drag) is one component of aerodynamic drag. The larger component of aerodynamic drag (for cyclists, due to their lower velocities) is the difference in air pressure between the front and rear of the rider.

The leading edges of a rider (front wheel, chest, arms and head) encounter high air pressure as the rider moves forward and forces the air to flow around and behind them. By contrast, the cyclist leaves a low-pressure void in his or her wake.

With high pressure in front and low pressure behind the rider, the cyclist is actually being dragged backwards by the differential in air pressure. This second component of aerodynamic drag is called pressure drag. Momentum, and the force of the rider's pedaling, continue to propel them forwards, but much of the rider's effort is now being spent fighting pressure drag in order to maintain and/or increase their velocity.

The diagram at right illustrates the kind (and levels) of drag experienced by different objects. The cylinder (a blunt shape) leaves a large and turbulent low-pressure wake as it moves through the air, which gives it a high degree of pressure drag. In the case of the streamlined "air foil" shape, wind flow stays attached to the shape without separating and becoming turbulent, which is why this kind of shape experiences relatively little pressure drag.

Drag Increases with Speed

The faster you ride, the more you struggle against aerodynamic drag; this is true because the power necessary to overcome aerodynamic drag is proportional to the cube of your velocity. In other words, to double your velocity, you need to exert eight times as much power.²

As all cyclists can attest, going faster takes tremendous effort; aerodynamic drag is the reason this is true.

Multiple studies, (Kyle, 1979 and Broker, 2003, for example) have quantified the aerodynamic benefits of drafting. One study (Kyle, 1979) found a 38 percent reduction in aerodynamic drag when the second rider stays within a foot of the leader's wheel.

This explains why the winning riders of mass-start races tend to stay out of the front ranks of the peloton for the majority of the event. Team leaders shelter themselves in their support riders' wakes, preserving their energy until crucial junctures late in the race. During the final sprint for the finish line, riders' speeds often exceed 30 miles per hour, so low aerodynamic drag is of the utmost importance.

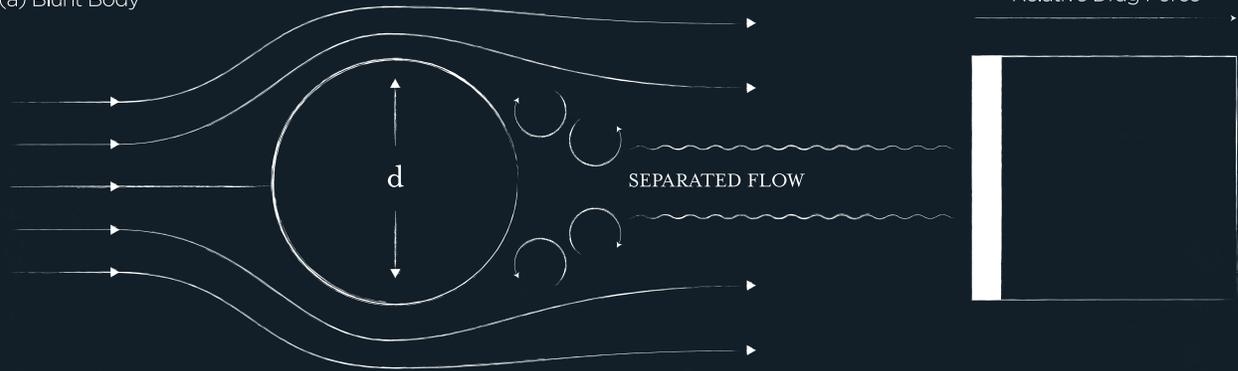
Similarly, in time trials, triathlons and other events in which a rider is racing against the clock and is not allowed to draft others, becoming as aerodynamic as possible becomes an absolute necessity.

²Glaskin, M. (2012) Cycling Science, pg. 130

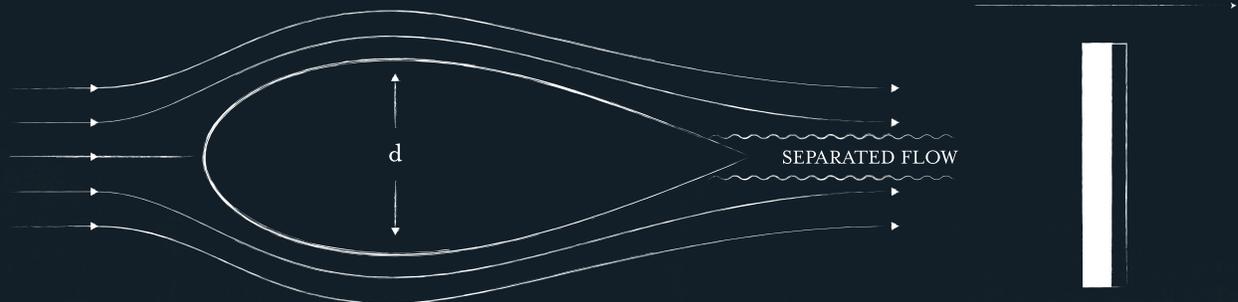
FRICTION DRAG AND PRESSURE DRAG

The diagram illustrates the kind (and levels) of drag experienced by different objects. The cylinder (a blunt shape) leaves a large and turbulent low-pressure wake as it moves through the air, which gives it a high degree of pressure drag. In the case of the streamlined "air foil" shape, wind flow stays attached to the shape without separating and becoming turbulent, which is why this kind of shape experiences relatively little pressure drag.

(a) Blunt Body



(b) Streamlined Body



CODE

■ Skin Friction Drag

□ Pressure Drag

The Two Keys to Reducing Aerodynamic Drag

Riders have attempted to go faster by reducing aerodynamic drag since the dawn of the modern bicycle. There are two primary ways to reduce drag:

1. Minimize the rider's frontal area; and
2. Streamline their shape.

To see why this is so, we can revisit the formula for drag in which aerodynamic drag force (F_D) can be expressed:

$$F_D = \frac{1}{2} \rho v^2 C_D A$$

F_D = drag force (N)

C_D = drag coefficient

ρ = air density

v = velocity

A = frontal area of the bike and rider

In this formula, there are only two factors that we, bicycle designers and riders, can change: the drag coefficient and the frontal area. Air density is affected by air temperature, pressure and humidity—three factors outside of our control. Velocity is not a factor to be tweaked, but rather the ultimate goal of the cyclist.

Reducing a Rider's Frontal Area

Riders can reduce their frontal area by getting “low on the bike”, positioning themselves with their arms and torso as parallel to the ground as possible. You can think of this as reducing the size of the cyclist or, more precisely, the amount of rider that the wind “sees”.

Reducing a Rider's Drag Coefficient

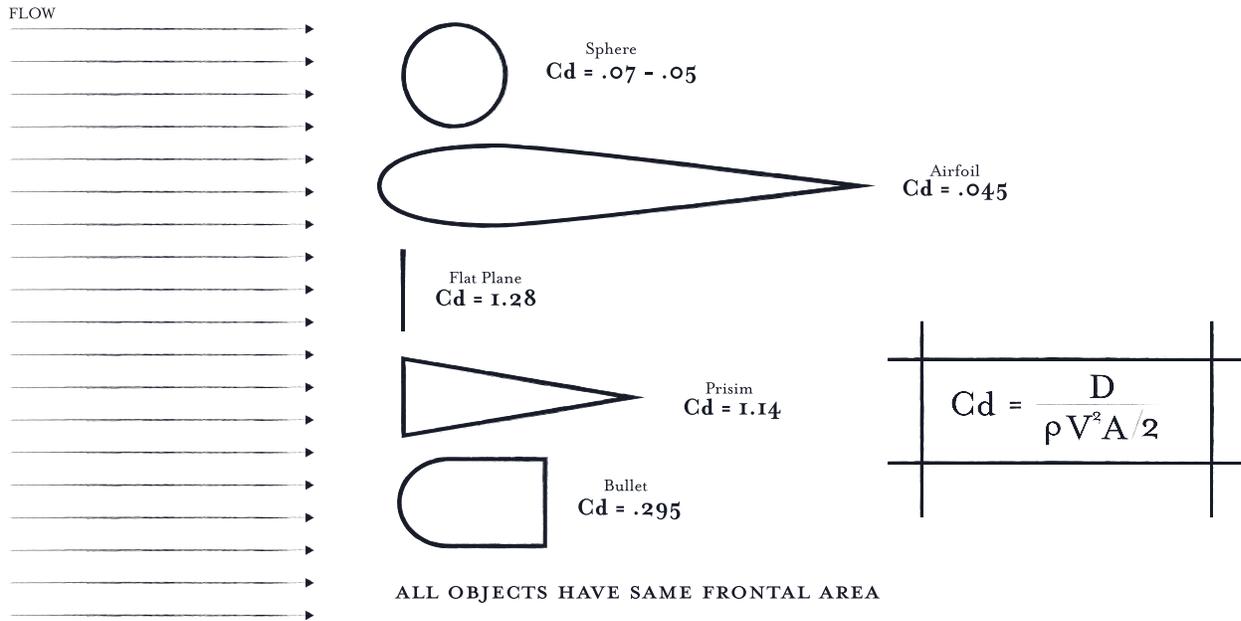
Riders can also try to reduce their drag coefficient by streamlining their shape. Drag coefficient is a measure of the shape of an object and how smoothly air flows around it. As noted earlier, non-streamlined objects leave large, low-pressure wakes behind them with a high coefficient of drag. Streamlined objects leave smaller wakes behind them and thus have lower drag coefficients and lower overall levels of drag. The following diagram illustrates how less streamlined objects leave larger, turbulent low-pressure wakes (which, again, increases their overall aerodynamic drag).

Your garden-variety brick—an aerodynamically-challenged an object if ever there was one—has a drag coefficient of 2.0. A Toyota Prius, by contrast, has an exceptionally low drag coefficient of 0.25, thanks to its streamlined, tear drop shape. The drag coefficient for a cyclist ranges anywhere between 1.15 and .88, depending on rider positioning and equipment choice.

The diagram on the opposite page shows how widely drag coefficient can differ, even among objects with identical frontal areas, but varying degrees of streamlining.

SHAPE EFFECTS ON DRAG

The shape of an object has a very great effect on the amount of drag.

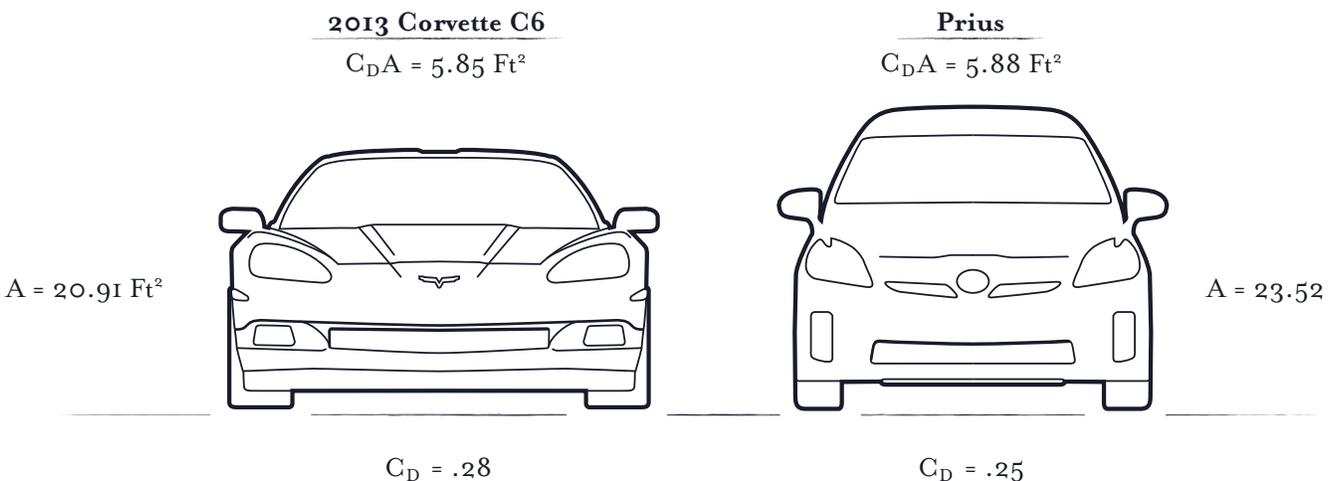


Size and Shape—Together—Determine Aerodynamic Drag

When people discuss the degree to which a product is aerodynamic, they frequently focus on the drag coefficient as the key indicator of a product's ability to cheat the wind. While the degree to which a product is streamlined has a huge influence on aerodynamic drag (see diagram above), it's worth remembering that both frontal area and drag coefficient work in tandem to influence overall aerodynamic drag.

Case in point, the Toyota Prius is often hailed as the most aerodynamic car on the road today because it possesses the undeniably low drag coefficient of .25. The streamlined 2013 Corvette C6, by contrast, has a drag coefficient of .28. Judging by these numbers alone, one could determine that the Prius is more aerodynamically efficient. But there's more to the story—size matters, too. Because the Corvette boasts a significantly smaller frontal area than the taller Prius (20.91 versus the Prius' 23.52) the Corvette comes out ahead, aerodynamically.

Or to put it another way, the drag coefficient isn't everything.



Rider vs. Bicycle Drag

Which is more important?

A bicycle accounts for 30 percent of the total aerodynamic drag. The rider, on the other hand, accounts for the remaining 70 percent of aerodynamic drag³. This is because, a cyclist's body, unlike a car or airplane, is a lumpy amalgamation of air pockets and non-streamlined shapes with a large frontal area to boot.

For comparison's sake, a typical passenger car has a drag coefficient in the range of .30 to .35⁴, while a rider atop a bicycle has a drag coefficient between .88 (racing bike, rider couched) and 1.15 (upright, commuting bike)⁵.

This also raises an excellent question: if the rider constitutes more than twice the drag of the bicycle and its components, why is there so much investment in aerodynamic bikes and parts? Shouldn't riders focus on making themselves more aerodynamic?

Yes and no.

While anyone interested in becoming more aerodynamic should certainly work on maintaining as low and streamlined a position on the bike as possible, actually doing so is easier said than done.

The most aerodynamic cycling position possible is rarely the most comfortable or, in real-world conditions, the safest, which is why aero bars are banned from mass-start races and only a handful of the most accomplished professional racers (Roger de Vlaeminck, Graeme Obree, Fabian Cancellara, etc.) can hold such a position for even an hour at a time. It's been reported, for example, that Chris Boardman couldn't walk upright for four days after setting the one-hour world record of 49.441 kilometers in 2000. What's more, the most aerodynamic positions often limit a cyclist's ability to breathe deeply and relax their upper body, both of which ultimately reduce the rider's power output and decrease velocity.

Clearly, there are limits to how aero the average rider can make him or herself. By contrast, any rider can significantly improve their aerodynamic advantage with key equipment choices. The challenge lies in determining which products truly are the most aerodynamic.

³ Gross, Albert C., Chester R. Kyle, and Douglas J. Malewicki. (1983). "The Aerodynamics Of Land Vehicles." Scientific American 249, no. 9 (December)

⁴ Shahbazi, K. (2007). Pressure Drag Reduction System with an Internal Duct.

⁵ Gross, Albert C., Chester R. Kyle, and Douglas J. Malewicki. (1983). "The Aerodynamics Of Land Vehicles." Scientific American 249, no. 9 (December)



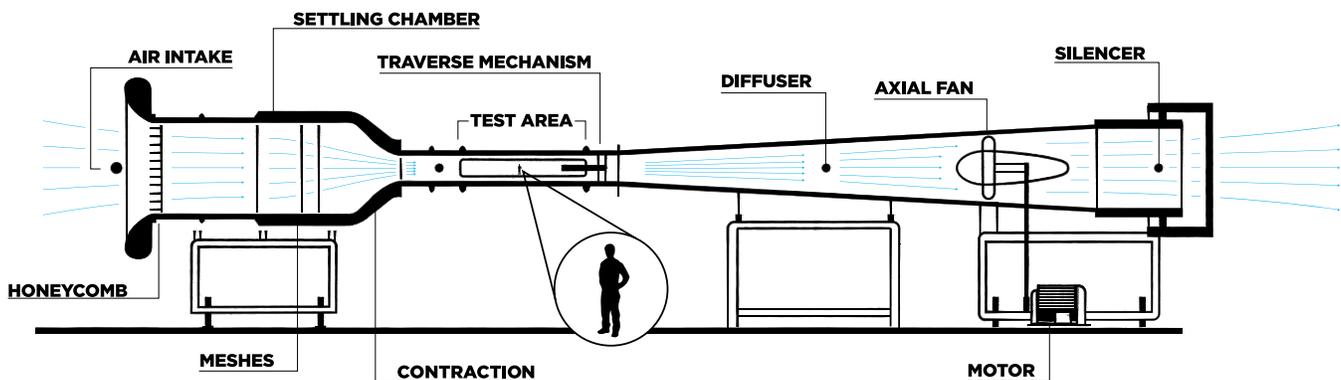
How Wind Tunnels Work

In order to reduce aerodynamic drag, you must be able to measure aerodynamic drag. That, again, is easier said than done. Since the late 1800s, wind tunnels have been the primary proving ground for testing and improving an object's aerodynamics. This is because gauging aerodynamic drag in "the real world" has proven nearly impossible. Natural wind sources are erratic. The wind changes force and direction constantly. Aerodynamic testing, by contrast, requires a constant, defined source of wind flow.

Enter the wind tunnel, essentially a tube equipped with powerful fans that blow (or, more commonly, pull) air over a fixed test subject, such as a bicycle. The air moving around the still object simulates what would happen if the object were moving through the air itself. Drag and side forces, as well as ambient air pressure and real-time air temperature and wind speed can all be measured in the wind tunnel. Most importantly, wind tunnel operators control the flow, direction and wind speed, entirely independent of natural weather conditions outside the tunnel.

While wind tunnels vary widely in size (some are small enough fit atop a desk while others are so large they can accommodate a passenger train), wind tunnels generally incorporate a few basic features (a settling chamber, contraction section, test section, diffuser and drive section) that help smooth and control airflow before it reaches the test subject.

Air is drawn into the settling chamber of the tunnel by an axial fan (which is typically at the rear of the tunnel). The settling chamber contains screens that help straighten and "settle" the air before it is forced into a narrowed section of the tunnel, called the contraction section, which increases airflow velocity before the wind hits the subject in the test section of the wind tunnel. The diffuser, mounted behind the test subject is used to slow the air's velocity without adding turbulence in the test section.



Ultimately, wind tunnels are designed to provide a consistent wind flow over the product within the test section. The device that actually measures a product's aerodynamic drag is the wind tunnel's multi-axis balance. The test subject is connected to this incredibly sensitive device (essentially a scale designed to work in multiple directions), which use strain gauges to measure drag, side force and lift at various angles of incidence. The multi-axis balance is, in many ways, the heart and soul of wind tunnel testing.





In North America a few popular wind tunnels include:

- San Diego Air & Space Technology Center Low Speed Wind Tunnel (LSWT)
- Kirsten Wind Tunnel at the Univ. of WA Aeronautical Laboratory (UWAL)
- A2 Wind Tunnel in Mooresville, North Carolina
- Wright Brothers Wind Tunnel, MIT
- Oran W. Nicks Low Speed Wind Tunnel, Texas A&M
- Glenn L. Martin Wind Tunnel, University of Maryland

Which Wind Tunnels Are Used by the Bike Industry?

Because bicycles travel at relatively low velocities, they are tested in low-speed wind tunnels, which have a maximum air speed of about 250 miles per hour. Due to the finely calibrated machinery, the costs to create and operate a quality wind tunnel—high speed or low—are quite substantial for most bike companies.

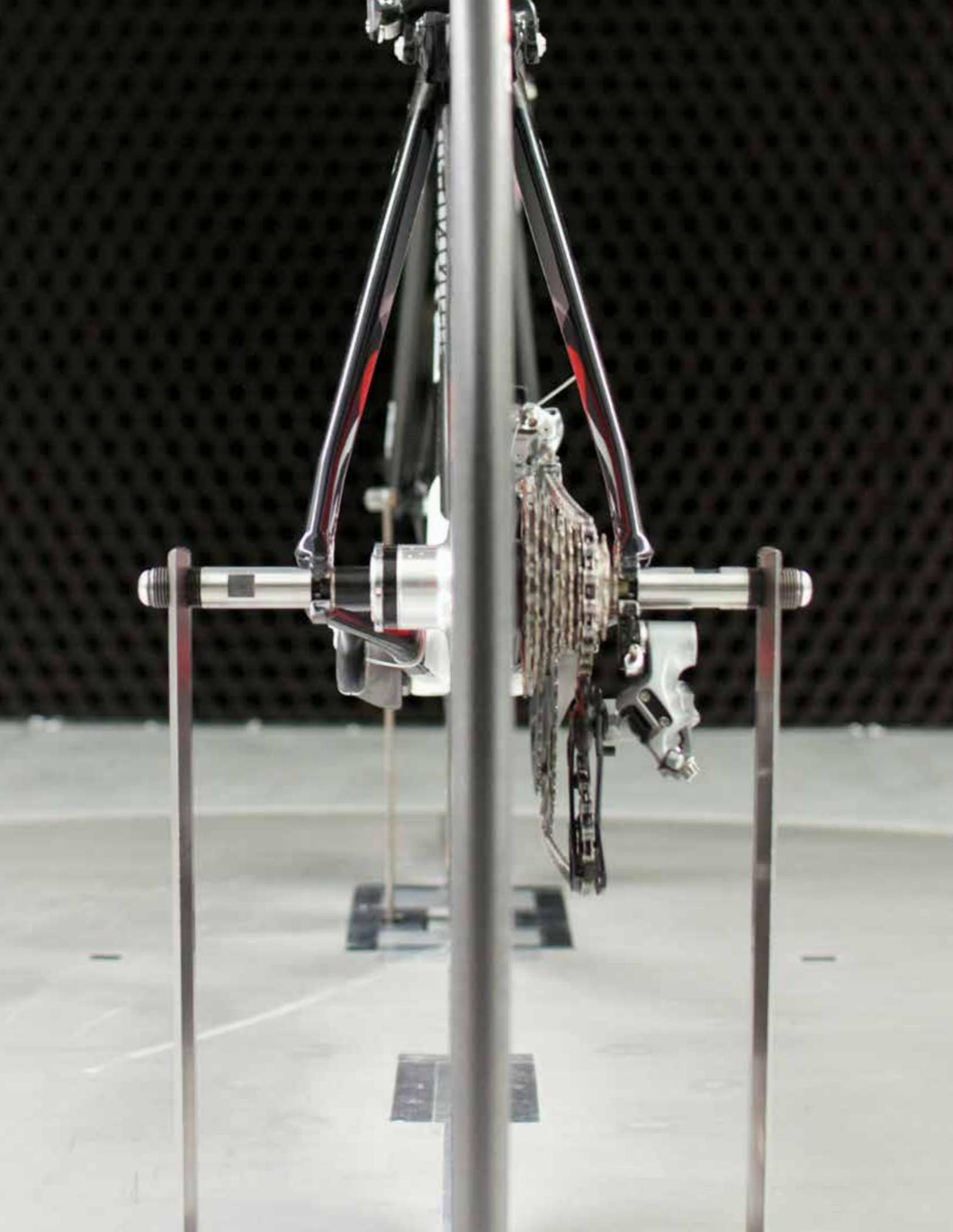
While the type of tunnel employed in testing bicycles is nowhere near as large as the type used to streamline space shuttles and Formula racing cars, they are still fairly massive. What's more, a wind tunnel's build precision must be incredibly high in order to provide repeatable results. Seemingly slight imperfections in the smoothness of the tunnel walls, for instance, cause erratic wind flow in the tunnel. Consequently, while almost anyone can build a wind tunnel, only a handful are actually considered reliable enough for use in the cycling industry.

Most wind tunnels feature some kind of fixture that elevates the bicycle from the test chamber floor in order to reduce the effect of the ground boundary layer, which might otherwise skew the test results. Likewise, wind tunnels generally incorporate some means of changing the bicycle's angle in relation to the wind flow and rotating the bicycle's wheels, so as to help mimic real-world conditions.

In addition to gleaning aerodynamic drag and side force figures, researchers can also visually track the air flow over their test subject by studying how smoke or dye in the air moves as it passes over the object. Similarly, tuft wands (essentially a small thread attached to a stick) are held over different parts of the object to see whether the airflow is laminar (flowing in smooth layers) or turbulent (swirling). Points at which the airflow changes from laminar to turbulent indicate spots where the airflow has become separated. Further streamlining the object's shape at these spots helps achieve a more laminar flow and, ultimately, reduces drag by decreasing the low-pressure wake.

Wind tunnels, in short, have been widely utilized because they are thought to provide consistent and reliable results that, theoretically, could be repeated and verified in a way impossible in the great outdoors.

Wind tunnels clearly have their advantages. Wind tunnels, and the way they are used, however, also have their drawbacks.



Limitations of Wind Tunnel Testing: Inconsistent Protocols

Wind tunnels can produce precise findings, but seemingly insignificant changes to the way that the test subject is arranged within the wind tunnel can lead to results that are (1) impossible to repeat and (2) of little use as a yardstick by which to compare similar products tested in other wind tunnels.

Or to put that in plain English—two wind tunnels can test the aerodynamic drag of the very same products and arrive at entirely different results.

Why?

There are no standardized testing protocols for wind tunnels and without universal protocols, there's no way of guaranteeing consistent, comparable results between one wind tunnel test and another.

Companies pay to have their products tested in wind tunnels and while they may receive advice on how to arrange their test session, they are ultimately free to gauge their products however they see fit. For that reason, a company that visits the same wind tunnel a day later with the goal of testing identical products might arrange the same test very differently, which would yield different—and potentially conflicting data.

Let's say that your goal is to test the aerodynamic drag of seven competing wheelsets. To do so, you'd have to determine which testing protocols would provide you with the most accurate results. Companies today employ radically different wind tunnel testing protocols. Here are just a few common approaches:

1. Wheel is tested alone (not attached to a bicycle) and unmoving.
2. Wheel is tested alone, but spinning.
3. Wheel is tested while fixed to a bike outfitted with a complete component group.
4. Wheel is tested while fixed to a bare frame and fork.
5. Wheel is tested while fixed to a bike outfitted with a test rider who pedals throughout the test.
6. Wheel is tested while fixed to a bike outfitted with a test rider who keeps the pedals horizontal for the test's duration.
7. Wheel is tested while fixed to a bike outfitted with a complete mannequin atop the bicycle.

These are just a few potential testing scenarios. Each with its own logic to recommend it.

Is keeping the frame bare of all other components—and rider—a gross simplification that takes the wheel out of its true context? It's conceivable, after all, that the addition of other parts (particularly brake calipers) will change the way air interacts with the wheels.

Alternately, if you add those components, you introduce confounding variables. Different component groups, in and of themselves alter the findings. Adding riders, who vary in size and shape and move the bike under pedaling efforts, contributes to the murkiness of the test results.

And these are gross factors with obvious impacts on testing data.... As we'll show in a moment, seemingly insignificant variations in test protocol can also lead to inaccurate and inconsistent test results.

Wind Tunnels Results Can Not Be Compared

Simple variations in wind tunnel design, and even the devices used to hold the test subject, can lead to conflicting test results. For example, if you change a tire's orientation (from left to right) the results of your aerodynamic tests will vary significantly—and this is even true with tires that appear perfectly symmetrical.

Likewise, the same product tested in the exact same way in the same wind tunnel—even on the same day—may yield entirely different drag measurements if the temperature within the wind tunnel changes significantly (which would affect the density of the air and the resulting aerodynamic drag). Qualified wind tunnel personnel adjust for any changes in air density, but these challenges give you an idea of the complexities that go unrepresented when you see a graph of aerodynamic drag.

Over the years, Easton has employed identical test protocols while testing wheels at different wind tunnels and found the variance between test results at those different wind tunnels to be so large as to make it impossible to meaningfully compare the data. In other words, even if companies agreed to employ identical testing protocols, the unique windflow characteristics within each wind tunnel would yield entirely different (and conflicting) test results.

Why does any of this matter? Wind tunnels are supposed to improve the accuracy of aerodynamic testing and, in many ways they do, but for all the reasons described above it's impossible to directly compare the results of one test to that of another with any real accuracy.

In the marketplace, the results from one wind tunnel test are often compared with those of another. Products are sold against one another based on this kind of data, but in truth, it's a bit like comparing apples and orangutans.

What is “Repeatability” & Why Does It Matter?

If it's impossible to compare the results of one test to another with any real validity, what is the point of even testing in the wind tunnel? Wind tunnel testing is still the most reliable means of measuring aerodynamic drag. While it's pointless to compare the results of one test to the results of a different test, component companies must still measure the drag of their products in an attempt to improve their aerodynamic efficiency. The goal, then, is to add validity, achieve accuracy and repeatability in the wind tunnel.

Accuracy is a fairly simple concept. Accurate results are results that truly match the outcome of product testing. In a wind tunnel, accuracy largely boils down to this question: is the multi-axis scale that measures drag properly calibrated? Is it accurately measuring drag forces? Better wind tunnels ensure that their equipment is properly calibrated and can provide proof that this is the case.

Repeatability is a slightly different, and more challenging, story.

Repeatability is really a measure of your testing precision. Repeatability is the ability to test a single product and arrive at the same values while repeating tests in the wind tunnel. Consistent, “repeatable” results are the hallmark of reliable testing.

Repeatability is what we are chasing in the wind tunnel. It's why we test our products at the same tunnel (the San Diego Low Speed Wind Tunnel) and it's why Easton always conducts several tests with the same set-up (same wheel, same tire, same frame) over the course of each day. We look at the drag curves from those several different tests and we check to make sure that the drag curves match up as closely as possible. We use these repeat tests to calculate a value that defines which differences in results (termed deltas) are significant. Highly repeatable results confirm that we are achieving precise and valid results.

Easton's Wheel-Testing Protocol: Maximizing Repeatability

Achieving repeatable results is a painstaking affair that requires real attention to detail and the best testing protocols possible. Over the course of several years we have employed several different testing protocols. Test protocols employed at one time or another include the following:

- Front wheel in strut (not attached to a bike fork and frame). Spinning and not spinning.
- Front wheel attached to complete bicycle (all components—bars, cables, etc.—installed).
- Front wheel attached to bicycle minus aero handlebars, cables, seat and seatpost
- Front wheel attached to bicycle minus bars, cables, seat, seatpost, cranks and derailleurs)



TMR time machine

BMC

BMC

BMC

BMC

TMR

TMR

WOLTER



One thing that we have noted over the years of testing products in a wind tunnel, is how critical it is to use the correct type of fixture to accurately simulate wind conditions. For evaluating front wheel designs we've determined that testing a sample in a bicycle (as opposed to a freestanding wheel in two struts) outfitted with no components other than brake calipers will provide the most accurate results.

With the front wheel in forks, the impact of the fork width and shape on wheel airflow is accurately simulated. We always test wheels in a frame and fork with no rider on the bike. We've found that having a rider present introduces so much variability into the test that it is no longer meaningful.

After comparing the results from scores of tests conducted over several trips to LSWT, we found that repeatability in wheelset testing was optimized when the wheels were rotating at a speed of 30 miles per hour and mounted to a bike frame (and fork) equipped with no components other than brake calipers. This setup allows for analysis of subtle design changes, allowing engineers to iterate toward the fastest shapes.

Additional steps Easton takes to ensure repeatable results include:

- (i) always testing with the same fixtures;
- (ii) using long data collection windows (up to 45-seconds);
- (iii) testing at multiple velocities and analyzing the results with linear regression;
- (iv) repeating the same test a minimum of three times and preferably 4 to 5 times a day (if possible);
- (v) rotating the front wheel;
- (vi) testing at multiple yaw angles;
- (vii) testing at the same tunnel (drag results at different tunnels can vary by +/- 10 percent; some of this is due to different fixtures);
- (viii) testing multiple samples of the same wheel to ensure that variances in manufacturing have no impact on test results;
- (ix) testing with a baseline "control" tire;
- (x) testing at high speed to maximize scale accuracy.

The Importance of Tire Selection

We test both our own wheels and our key competitors' wheels with a wide range of tires from different manufacturers and have found that tire selection has a tremendous impact on the aerodynamic drag of a wheel, based on its size and shape.

Some wheelsets exhibit very low drag with one brand of tire and fairly high drag with the next. This fact alone can significantly skew the results of wheelset testing. Particular care, then, should be paid to testing a wide range of tires and also selecting a baseline "control" tire for direct, "head-to-head" comparisons of competing wheelsets.

Why Is Test Protocol So Important?

Test protocol matters because the real differences in the aerodynamic efficiency of modern wheels are, in truth, quite minimal and if you want to uncover the real differences in performance from one wheel to the next, precision is absolutely critical.

In recent testing at the San Diego Low Speed Wind Tunnel, we had repeatability of plus or minus 6 grams (95% confidence interval). If the drag of two wheels is within 11-grams, those two wheels are considered statistically the same. **For most riders, a 10-gram difference in drag will amount to a 4.6 second time saving over a 40-kilometer individual time trial.**

High Costs Limit Wind Tunnel Testing

Wind tunnels are expensive and this limits the degree to which some companies actually employ them. At present, companies and individuals can expect to pay between \$390 and \$1,500 per hour to use a wind tunnel. When you add in travel to the site, staff time and several hours (or days) of testing, the cost of even a single session at a wind tunnel quickly becomes prohibitive. Limiting the amount of time spent in the tunnel, however, inevitably limits the rigor with which some products are tested.



INERTIA (PER VOLUME) DIVERGENCE OF STRESS

$$\rho \left(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{UNSTEADY ACCELERATION}} + \underbrace{\mathbf{v} \cdot \nabla \mathbf{v}}_{\text{CONVECTIVE ACCELERATION}} \right) = - \underbrace{\nabla p}_{\text{PRESSURE GRADIENT}} + \underbrace{\mu \nabla^2 \mathbf{v}}_{\text{VISCOSITY}} + \underbrace{\mathbf{f}}_{\text{OTHER BODY FORCES}}$$

Computational Fluid Dynamics

Great Potential But No Replacement for the Wind Tunnel

In recent years, computer modeling or computational fluid dynamics (CFD) has grown in importance as a tool for testing aerodynamic drag as well as vertical and side forces.

CFD programs continue to improve and as they do, will be increasingly employed within the cycling industry. As it stands, CFD offers engineers the ability to wed Computer Aided Design (CAD) programs and CFD programs and infinitely tweak—in a virtual setting—the test conditions and the shape of their product. Ultimately, this reduces the number of prototypes that must be fabricated and tested.

However, while some observers have suggested that CFD might one day make wind tunnels obsolete, there's little chance of that proving true, at least in the foreseeable future. For starters, CFD programs are still quite expensive. The well-respected Fluent program, for instance, retails for upwards of \$75,000 and carries an \$11,250 annual licensing fee. That, to be blunt, would buy you quite a lot of time in a wind tunnel.

Running a simulation is also a fairly time-consuming process—even with a high-powered computer, a simulation of a single wheelset, for instance, can take up to week to complete.

Finally, and most importantly, CFD programs are not the best tool for modeling drag of certain bicycle components, such as wheels. In order for a CFD simulation to provide reliable results, the engineer must accurately model the flow of air around a wheel in a wide range of conditions. This is difficult to do with a spinning object, especially when spokes and airflow through a frame/fork are introduced.

Engineers using CFD programs must be able to apply a mesh around an object in order to set up calculation cells that will then calculate how turbulence will develop over that segment of the mesh; while that works well with a static object, such as an F1 car body, it does not work well with turning wheels...or any object that moves or changes shape.

Finally, engineers must still validate their products in a wind tunnel setting. Wind tunnels, as flawed as they can be, will remain the primary aerodynamic testing ground in the cycling industry for the foreseeable future.

Yaw: Adding Even More Confusion to the Mix

Yaw, adds yet another degree of confusion to the matter of aerodynamics. Or to put that more plainly, how engineers account for and test a product's aerodynamic drag in cross-wind conditions also leads to some confusing information about which cycling products are truly the most aerodynamic.

As cyclists we rarely spend the entirety of a ride pedaling directly into a headwind. At times, it may feel that way, but the wind blowing against a cyclist's face is oftentimes actually the air the cyclist displaces as they pedal along. The actual meteorological wind is constantly shifting its speed and direction (as is the cyclist) over the course of a typical ride.

At any given time, a cyclist feels the effects of two different "wind" sources: the air they displace and the wind that strikes them from an angle other than straight ahead (zero degrees). Those two types of wind combine to make an effective wind felt by the rider and the angle that this effective wind hits the cyclist at is called the yaw angle. The yaw angle is also impacted by both the wind speed and the cyclist's own speed.

In short, yaw angle is determined by four things:

- Rider speed
- Wind speed
- Rider direction
- Wind direction

Yaw is almost always present because wind speed is rarely zero and a rider's direction rarely aligns perfectly with the wind. Cyclists commonly experience yaw angles of up to 20 degrees. Yaw angle decreases as rider speed increases and as a result, faster cyclists averaging more than 20 miles per hour generally experience a narrower range of yaw angles.

The following table summarizes the maximum yaw angle a cyclist might experience given the wind speed and their own rate of travel.

Why does yaw matter? Yaw angles matter because aerodynamic drag is affected by yaw. Let's consider bicycle wheels. Early research showed that traditional, box-section rims had very high drag coefficients in crosswinds and that aero-style rims exhibited less drag under the same conditions. Accordingly, engineers seeking to make the most aerodynamic wheelset possible test their products at a variety of yaw angles (usually 0 to 20 degrees) and will often optimize their rim shapes to perform best at certain yaw angles.

In the market place, this leads to confusion. Multiple component and bicycle manufacturers market their product as "the fastest" or "most aerodynamic", but at what yaw angle is this true? And if they do list that yaw angle, does this actually clarify anything for cyclists?

What does it actually mean to the typical consumer that a particular wheelset is most aerodynamic at ten, or seven or five degrees of yaw? Are these conditions that this particular consumer actually experiences on their rides? It's not as if the wind hits a cyclist from one angle all day. Besides, as all cyclists know, wind conditions and rider velocity vary tremendously—what kind of yaw angle should matter to them?

Even if we assume that wind tunnel testing results are uniform, repeatable and comparable (which, as discussed earlier, is not the case) the matter of how yaw is accounted for in product design and eventually marketed to consumers muddies the waters for anyone looking to gain the greatest aerodynamic benefit from their bicycle or component choice.

Engineers face a conundrum—crosswinds clearly must be accounted for in their design process, but how? Easton recommends Wind Averaged Drag.

	Cyclist Speed (Vc)	Wind Speed (Vw)	Max Yaw angle (B)	Rider Type
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AVERAGE WIND
AVERAGE WIND TUNNEL
WIND SPEED

30 mph	6.6 mph	12.7 deg	Pro Rider
25 mph	6.6 mph	15.3 deg	Fast Rider
20 mph	6.6 mph	19.3 deg	Good Rider
15 mph	6.6 mph	26.1 deg	Average Rider
10 mph	6.6 mph	41.3 deg	Slow Rider

← **Most Common**

LOW WIND
AVERAGE WIND TUNNEL
WIND SPEED

30 mph	3.3 mph	6.3 deg	Pro Rider
25 mph	3.3 mph	7.6 deg	Fast Rider
20 mph	3.3 mph	9.5 deg	Good Rider
15 mph	3.3 mph	12.7 deg	Average Rider
10 mph	3.3 mph	19.3 deg	Slow Rider

HIGH WIND
AVERAGE WIND TUNNEL
WIND SPEED

30 mph	9.9 mph	19.3deg	Pro Rider
25 mph	9.9 mph	23.3 deg	Fast Rider
20 mph	9.9 mph	29.7 deg	Good Rider
15 mph	9.9 mph	41.3 deg	Average Rider
10 mph	9.9 mph	81.9 deg	Slow Rider

EXTREME WIND
AVERAGE WIND TUNNEL
WIND SPEED

30 mph	30 mph	89.5 deg	Pro Rider
25 mph	30 mph	89.6 deg	Fast Rider
20 mph	30 mph	89.8 deg	Good Rider
15 mph	30 mph	90.0 deg	Average Rider
10 mph	30 mph	90.0 deg	Slow Rider



Wind Averaged Drag: A Better Approach

Manufacturers tend to measure aerodynamic drag at discrete yaw angles and provide consumers with tables or graphs comparing each product's aerodynamic drag value at each yaw angle.

An example on the facing page.

This kind of analysis leads to the claims that Product C has the least drag at 10-degrees of yaw. Or that Product D is "the fastest" at 0-degrees of yaw. These figures, while potentially accurate, don't actually make much sense to consumers who generally can't recount the yaw angles they encountered on their last ride. Nor do these figures answer the question of which product is actually the most aerodynamic overall (that is, in most conditions).

One of our goals at Easton Cycling is to advance aerodynamics by promoting a more user-friendly and consistent means of measuring and comparing aerodynamic drag. To that end, we have adopted Wind Averaged Drag (WAD).

The History of Wind Averaged Drag

Wind Averaged Drag is an analytic tool originally developed⁶ within the automotive industry during the energy crisis of the 1970s by researcher, Ken Cooper. Cooper, who specialized in studying fuel economy, sought a means of simplifying research on automotive drag and its impact on fuel-efficiency.

In a nutshell, WAD is a formula that aggregates the drag measurements from several discrete yaw angles into a single "wind averaged" measure of drag.

The logic behind averaging drag is as follows: a car can, theoretically, be exposed to a wide range of yaw angles while it travels from walking speed to highway speeds. However, cars traveling at highway speeds actually experience a very narrow range of yaw. To wit, there's less than a 10 percent probability of experiencing a yaw angle of more than 10 degrees when you travel in a car at 55 miles per hour.

Thus, Cooper realized that if engineers wanted to make a car more aerodynamic and energy efficient at highway speeds, they should focus on reducing drag at the yaw angles a car actually experiences at highway speeds. Or to put it simply, you don't design a car to be aerodynamic at speeds of just five miles per hour.

⁶Cooper K. SAE Wind Tunnel Test Procedure for Trucks and Buses. SAE Recommended Practice J1252; 1979: August

⁷Cooper K. Truck Aerodynamics Reborn—Lessons from the Past. SAE International Truck and Bus conference and exposition. SAE 2003-01-3376, Houston, TX; 2003 Nov.

Typical Drag vs. Yaw Angle Plot



The graph above is the typical way of showing a product's aerodynamic performance. The table below uses Wind Averaged Drag. Which do you find easier to read? Easton is willing to bet that you'd rather see a calculated average with a listing of time saved in a race simulation.

Wind Averaged Drag Analysis

Model	WAD at 30mph	Time Saved Over 40k Time Trial at 30mph*
A	554.5	-2.5 sec
B (Baseline)	547.5	0.0 sec
C	504.1	16.0 sec
D	505.8	15.4 sec

*Time saved vs. baseline model

**WAD answers the question:
On average, which bike or component
is going to be the most aerodynamic
in most conditions?**



Input Data

Bike speed over ground (V_b)	30.0	mph
Mean wind speed (V_{wt})	7.0	mph
Mean wind speed (V_w)	6.6	mph
Bike speed over ground (V_b)	13.4	mph
Mean wind speed (V_{wt})	3.1	mph
Mean wind speed (V_w)	3.0	mph

Bike Axis Drag Data	
Yaw [deg]	Drag [g]
0	488.821962
5	498.639393
7.5	465.998012
10	418.423174
12.5	383.4985
15	367.731189
20	455.037938

Calculated Outputs

Wind Averaged Drag	465.0 [g]	1.03 [lbf]
Maximum Yaw Angle	12.7 [deg]	



Applying WAD to Bicycles and Cycling Components

Wind Averaged Drag was introduced to the sporting goods industry by aerodynamicist, Len Brownlie. Brownlie is an aerodynamicist with 20 years of experience with wind tunnel testing and a client list that has included Nike, the United States Olympic Cycling Team, the Canadian Olympic Committee, the United States and Dutch Speed Skating Teams, and countless high-profile professional athletes. Brownlie began working with Giro Cycling in 2004 and Easton Cycling in 2008. It was in 2009, however, that Brownlie adopted WAD as a means of improving the testing and development of Giro's Air Attack helmet (8). Brownlie has since employed WAD to optimize the aerodynamics of Easton wheels.

Brownlie, like countless engineers before him, found (during wind tunnel testing) that every helmet had a "sweet spot"—a yaw angle at which it exhibited very little aerodynamic drag. This kind of data, however, provided Brownlie and the Giro researchers with no means of determining which helmet was actually the most aerodynamic most of the time. Brownlie sought a simple and reliable metric that would answer this question and had been considering WAD for some time. In 2009, Brownlie contacted Cooper, who, along with researcher Dr. Peter Ostafichuk of the Department of Mechanical Engineering, University of British Columbia, helped adapt WAD to the measurement of drag in cycling.

The WAD calculation for cycling is essentially the same as the one used by Cooper for the study of fuel efficiency. The key difference is that the original calculation was predicated on an average wind speed of 7.0 miles per hour, which is what a semi-truck (Cooper's primary area of focus) generally experiences. Cyclists, however, are situated closer to the ground and, thus, typically experience a slightly slower average wind speed of 6.6 miles per hour.

Though WAD has its origins in the automotive world, the logic holds true for cycling aerodynamics. Per the table on page 27, a very slow rider (one traveling 10 miles per hour) could experience a yaw angle of as much as 90 degrees while riding in gale force winds. The cycling industry, however, does not design aerodynamic products to suit those conditions. Not by a long shot.

Most companies today assume a rider velocity of 30 miles per hour while calculating aerodynamic drag—and while it's worth debating whether or not that velocity is too high for products geared to the average consumer (20 miles per hour, might for instance, be a more realistic rider speed), 30 miles per hour is essentially the industry standard reference velocity.

What kind of wind speeds do cyclists ride in? Clearly, wind speed varies based on region, but the average wind speed that a cyclist experiences in North America is 6.6 miles per hour, which makes it the most sensible choice to use in the calculation.

⁸Len Brownlie, Peter Ostafichuk, Erik Tews, Hilgard Muller, Eamon Briggs, Kevin Franks—The wind-averaged aerodynamic drag of competitive time trial cycling helmets. ISEA 2010.

Per the same table on page 27, a rider traveling at 30 miles per hour and encountering winds at 6.6 miles per hour would, experience a maximum yaw angle of 12.7 degrees. In applying WAD to cycling, then, we start out by recording drag values of a bike or component at 0, 5, 7.5, 10, 12.5, 15, and 20 degrees of yaw. The calculations proceed with linearly interpolating this raw drag data so that we can infer the drag between the seven measured yaw angles. Next, the resultant yaw angle and corresponding drag value are determined for each possible wind direction (in relation to the rider direction in five degree increments from 0 through 360, commonly referred to as 'theta'.)

The Wind Averaged Drag figure reported is an average of these 72 values. WAD effectively simulates the 'average' drag for the life of a product exposed to all possible wind conditions. The example on the facing page shows the drag recorded for a product at 0, 5, 7.5, 10, 12.5, 15 and 20 degrees of yaw, assuming a rider velocity of 30 mph and average wind speed of 6.6 mph. The WAD formula aggregates the drag for every yaw angle—between 0 and the maximum yaw of 12.7-degrees—and provides a single Wind Averaged Drag figure of 465 grams.

Is this product more or less aerodynamic than a competing product? To find out, we'd simply use the WAD calculator to aggregate the drag measurements obtained for the second product under the same wind tunnel conditions. The product with the lower average drag figure is, on the whole, more aerodynamic.

One number tells the entire story.

WAD allows aerodynamic drag to be reported in grams. Watts and time saved over the course of a ride of a certain distance can be extrapolated using assumptions of steady state, flat course (no elevation change) and standard rolling resistance. For most riders, a 10-gram difference in drag will amount to a 4.6 second time saving over a 40-kilometer individual time trial. The bottom line, however, is that Wind Averaged Drag eliminates the need for confusing graphs of "spaghetti data" and defines aerodynamics in a way that is consistent, realistic and relatable.

WAD answers the question: On average, which bike or component is going to be the most aerodynamic in most conditions? That, after all, is what consumers want to know when they are looking to increase their velocity and reduce their effort on the bike.

Cross-wind Stability

More and more riders are seeking wheelsets that are not only "fast" due to reduced drag but also "stable". Cross-wind stability is a very real and desirable trait in a wheel—it is, however, also something that is quite difficult to model and test for.

What does "stable" mean? If you are riding in gusty conditions, your effective wind angle changes and your front wheel will constantly experience changing side forces, which can be felt through the handlebars. In extreme cases, riders may be forced to suddenly correct the steering in order to continue in a straight path. Anyone who has been passed by a semi-truck on a windy day has probably experienced that small moment of panic when this occurs. It's not a confidence-inspiring sensation. In steady side winds, riders may also have to steer into or away from the wind to balance the bike. Neither situation makes riding a bike effortless or fun.

When deep section "aero" rims first hit the market, there was a common perception that deeper-section rims invariably exhibited poor cross-wind stability. As the field of "aero" wheels has matured, it has become clear that the depth of the rim is not the only factor at play in the matter of stability.

The more accurate way of evaluating cross-wind stability is to measure the center of pressure on the front wheel and determine how much of a steering force is required to maintain a rider's line as the wind force and angle changes. This, however, is also easier said than done.

To date, some companies in the bicycle industry have employed CFD to help gauge steering force, but as is the case with modeling aerodynamic drag, CFD analysis requires perfect assumptions in order to provide reliable results and, thus, leaves much to be desired here. At least one company claims to have also devised a specific test for cross-wind stability, but the testing protocol is not public, which requires consumers to accept the claims of superior stability at face value.

What we, at Easton Cycling, have reliably found is that certain "clean" shapes (typically blunt-profile rim sections) exhibit greater stability in cross winds. We have not, however, devised a test that we feel easily and accurately predicts cross-wind stability. Such a test would be an asset to the cycling industry.

WAD CALCULATIONS

INPUT DATA

Bike speed over ground (V_b)	30.0 MPH
Mean wind speed-atmospheric (V_{wt})	7.0 MPH
Mean wind speed-within boundary layer (V_w)	6.6 MPH
Bike speed over ground (V_b)	13.4 M/S
Mean wind speed-atmospheric (V_{wt})	3.1 M/S
Mean wind speed-within boundary layer (V_w)	3.0 M/S

BIKE AXIS DRAG

Yaw (deg)	Drag (g)
0	488.8
5	498.6
7.5	466.0
10	418.4
12.5	383.7
15	367.7
20	455.0

OUTPUT CALCULATIONS

Wind Averaged Drag **465.0** (g) **1.03** (lb)

Maximum Yaw Angle **12.7** (deg)

Conclusion: Lessons from the Wind Tunnel

Our goal with this white paper is to accurately convey the manner in which the cycling industry tests aerodynamics and reports their findings. While we understand that many researchers do their best to accurately measure aerodynamic drag and design the best products possible, the current metrics and the way they are used to market products are confusing to consumers and engineers alike.

All products perform well at specific yaw angles, but to suggest that any product is “best” because it performs well at a specific yaw between 0 and 20 degrees is, ultimately, misleading. Only one product can be “the most aerodynamic”. As it stands, countless products in any one category are given that title, which only serves to make the entire prospect of measuring aerodynamic drag seem suspect. Furthermore, the consumer is given no clear means of parsing the data, or they are left to compare data from different wind tunnel studies, which is also fruitless.

This is what we advocate:

The adoption of Wind Averaged Drag

Consumers seeking an aerodynamic edge need a single metric to help them determine which product is best for them. Wind Averaged Drag is perfectly suited to this. It is accurate. It makes sense. We suggest that other cycling brands utilize the WAD formula to demonstrate test results.

Transparency in Testing Protocols

Under what conditions are bikes, apparel and components being tested? Companies rarely make their testing procedures available to the public. This must change. While we, at Easton Cycling, are confident in the reliability of our own testing protocols and have therefore made them available to the public, we are advocating for a set “best practices” for wind tunnel testing.

We respect the fact that other companies will come to different conclusions about the best approach to achieving reliable test results—we simply ask that the approach be made transparent so that consumers have yet another means of gauging the validity of wind tunnel results. If you test wheels in a wind tunnel, for instance, do you test the wheel attached to a bike or by itself in stand? If you design bike frames, do you test the frame by itself or with a rider or mannequin aboard? We are not suggesting a single “correct” response to any of these questions—we are simply advocating that our contemporaries make their protocols clear to the public.

Ultimately our goal at Easton Cycling is to educate and inform the marketplace. Understanding the entire landscape of aerodynamic products will help consumers decide which wheelset (or bike or helmet) serves their specific needs best



