WHITE PAPER

SYSTEMSIX

cannondale

Table of Contents

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Executive Summary

The all-new SystemSix is here. So are the test results. And we're proud to say that this race-bred speed machine is absolutely the lowest-drag, most efficient, all-around fastest UCI-legal road bike on the market today. Not only the fastest in the wind tunnel. Not only the fastest for a select few riders in a select few scenarios, but the fastest for anyone interested in going faster, just about everywhere you'd want to go faster. Call it drag reduction. Call it aerodynamic advantage. We call it free speed, and it is the culmination of a multi-year, systemwide approach to efficiency and real-world performance. Proving just what can be accomplished when the entire machine - not just the frame and fork - is optimized for fast. Delivering real speed for real riders.

Overview

SystemSix was designed to be the fastest road bike on the planet. This is a bike designed to deliver more speed, more of the time. This is not just a bike for racers, but anyone who likes to go fast.

SystemSix is a complete bicycle system with each component optimized in pursuit of speed, without sacrificing any of that classic race bike feel. SystemSix comprises six unique elements:

- Frame
- Fork
- Seatpost
- Stem
- Handlebar
- Wheels

When setting out to design a bike with the ultimate pursuit of speed it is first important to understand what it is that makes a bike and rider fast. This all begins with the six elements of cycling resistance – these are the resistive components that work against you as a rider. Minimizing these will make you faster for the same effort, or allow you to maintain the same speed with less effort.

Cycling Performance

How do we determine cycling performance?

Cycling performance can be described by a balance of input power against resistive forces. There are six resistive loads acting on a bicycle and rider system. These are:

- Rolling resistance
- Wheel bearing friction
- Drivetrain friction
- Aerodynamic drag
- Potential energy – the energy you expend to climb
- Kinetic energy – the energy you expend to accelerate

These six terms are related by the cycling power equation. This is a scientifically validated equation derived by Martin et al. (1998) that describes the resistive power terms:

$$\eta . P_{Athlete} = P_{NET} = P_{Aero} + P_{RR} + P_{WB} + P_{PE} + P_{KE}$$

Where;

Aerodynamic Resistance:	$P_{Aero} = C_D A \frac{1}{2} \rho V_A{}^2 V_R$
Rolling Resistance:	$P_{RR} = \mu (m_B + m_R) g.\cos(\tan^{-1}(G))\, V_R$
Wheel Bearing Resistance:	$P_{WB} = (91 + 8.7 V_G).10^{-3}.\, V_R$
Resistance Due to Altitude Gain:	$P_{PE} = (m_B + m_R) g.\sin(\tan^{-1}(G))\, V_R$
Resistance Due to Acceleration:	$P_{KE} = \frac{1}{2}(m_B + m_R + \frac{I}{r^2}) \frac{(V_{R2}{}^2 - V_{R1}{}^2)}{(t_2 - t_1)}$
Drivetrain Efficiency:	η

Using this equation, we can take a detailed look at the interaction between resistive loads in cycling. This gives us a better understanding of how each element affects cycling performance so we can work to minimize those that have the greatest influence. Note that the drivetrain efficiency is represented by a single scaling factor, η, not a separate term. This is because drivetrain efficiency is most commonly represented as a percentage of the input power.

Speed and Power

Aerodynamic power is a cubic function of velocity (this can be seen in the power equation on previous page). This means that aerodynamic power increases much more rapidly than the other resistive terms. This fact is now generally understood by the cycling community. However, it is also the origin of a common misconception that aerodynamics is only important at high speed. As can be seen in **Figure 1**, aerodynamic resistance increases its proportion of total resistance as your speed increases. But this is not to say that it is only important at some arbitrary high speed. A more useful approach is to consider aerodynamic resistance as a percentage of your total power as a rider. This is shown in **Figure 2**.

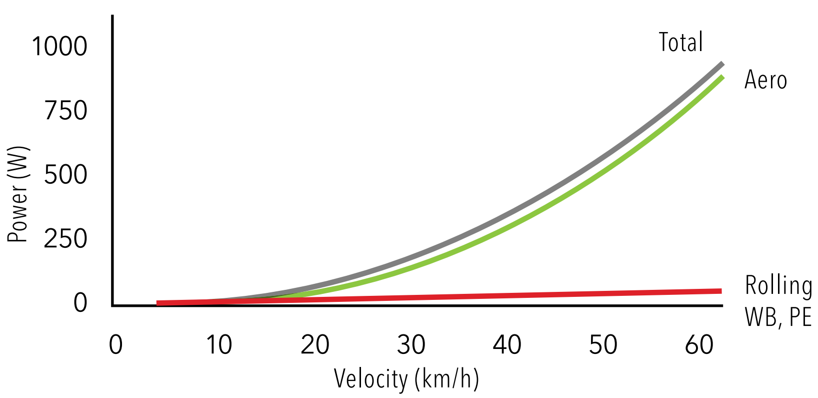


Figure 1 – Cycling power breakdown with velocity.

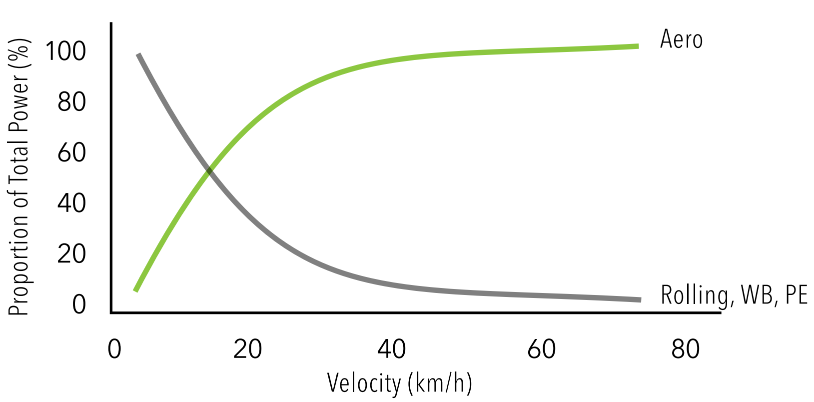
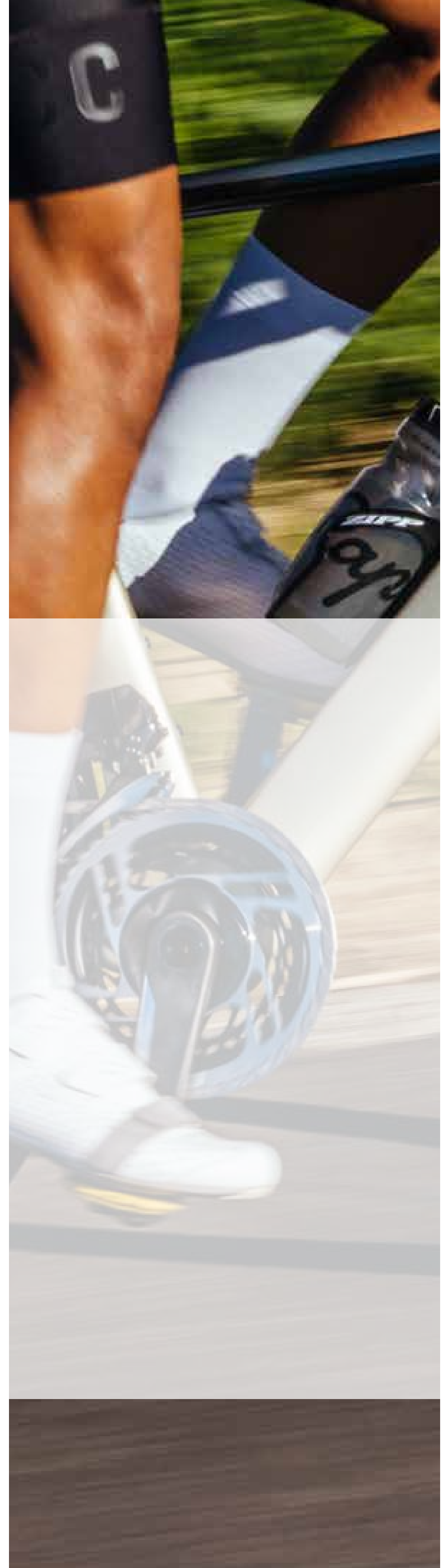


Figure 2 – Resistive elements proportion of total power with increasing velocity.



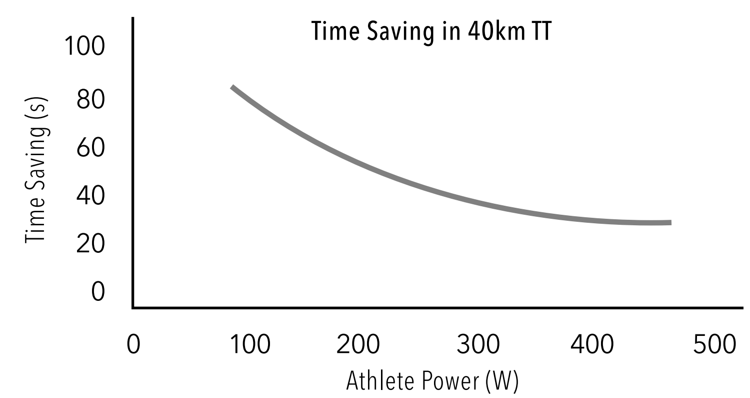


Figure 3a – Time saving for athletes of varying power levels over a 40km time trial given a drag reduction of 0.015m^2.

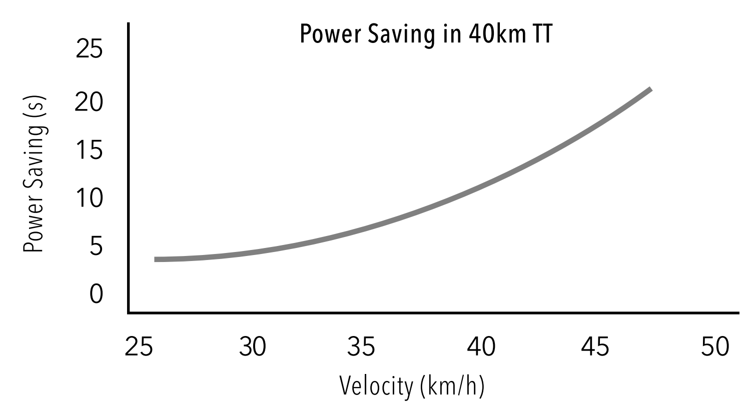


Figure 3b – Power saving for riders at different speeds given a drag reduction of 0.015 m^2.

When shown as a percentage of total it is seen that aerodynamic resistance is more than 50% of total power at speeds above 15 km/h (~9 mph). This means that aerodynamic drag has a large impact on cycling performance at all levels. Remember that 15 km/h is the cross over point. Below this, aerodynamic drag is still providing resistance on the bicycle and rider. Since aerodynamics is a function of velocity, as soon as you start moving, aerodynamic drag is working against you.

This data is calculated using typical road cycling values in the cycling power equation. In these examples we are considering a flat road, so the Potential Energy (PE) term is zero. We are also considering steady state riding (no acceleration) which means the Kinetic Energy (KE) term is also zero. This is a general assumption to look at the influence of other factors but is a reasonable model for many cycling scenarios. Input parameters for the equation are typical values for a road rider and are listed in **Appendix A**.

It is worth making one more point on the influence of aerodynamics on riders of differing speeds. It is still sometimes quoted that aerodynamics only matters above a certain speed and therefore aerodynamic performance is only relevant to elite athletes. Consider the power equation, the aerodynamic power term is a cubic function of velocity. This means that for a given aerodynamic saving, a faster rider will have a larger power saving. However, the opposite is true for time savings. Because a slower athlete spends more time on course, the equivalent drag saving actually results in a larger time saving than for the faster athlete. For example, consider a saving of 0.015 m^2 and riders completing a 40 km time trial. The power saving and time saving over that event are plotted in **Figures 3a** and **3b**, using some typical input parameters for the power equation. The data shows that while the less powerful rider is slower, they save more time over a fixed distance event. This further highlights how all road riders can benefit from aerodynamic savings.

The Influence of Gradient

So far, we have looked at data for riding on a flat road with increasing velocity. The obvious question then is: what happens when we start climbing?

Figure 4 applies the same approach as used earlier, and calculates power distribution for increasingly steep gradients. Each column in the graph represents the distribution of power at a given gradient. In this case we are considering a rider with a steady 300 watt output. It is intuitive to see that as gradient increases more of your power is spent overcoming the gradient (potential energy term). It also follows that your speed will drop as gradient increases. Since aerodynamic drag is a function of velocity (and not mass or gradient) this means that the aerodynamic power term also decreases. Looking closely you will also note that rolling resistance decreases, because power consumed by rolling resistance is a function of velocity: as speed drops on the climb, so does the corresponding power term.

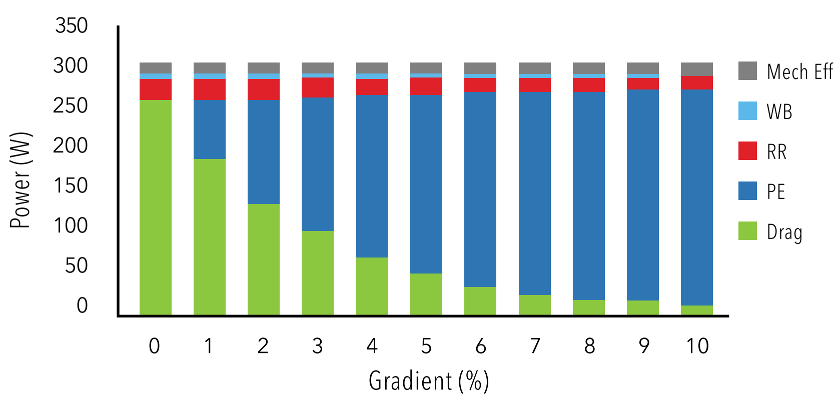


Figure 4 – Distribution of power across each resistive term with increasing gradient.

The power equation shows us that the primary input in the potential energy term is mass. Gradient and speed are clearly important, but are a function of the road, not the part we have control over. So, the big questions is, which has the largest benefit in terms of performance; aerodynamics or mass? The equation shows us that, all things being equal, lower mass will always be preferable. But what about when things aren't equal? Very rarely in design can you achieve the lightest weight without sacrificing some other area of performance. Similarly, typically optimizing for aerodynamics requires increased surface area as sections are shaped to better move through the air. This greater surface area usually means an increase in weight. It is, therefore, important to consider how weight and aerodynamic savings interplay on overall performance and ultimately speed.

The Tipping Point

One of the most useful tools for assessing the interplay between weight and aerodynamic optimization is to look at two possible configurations and determine the gradient at which the weight saving become more beneficial to performance that the aerodynamic saving. On flat roads mass has very little impact and so aerodynamic savings will always have a greater impact on performance. As gradient increases we will reach a break even point at which the aerodynamic saving and weight saving provide equal performance. Only above this gradient is a weight saving benefiting performance. **Figure 5** below compares SystemSix against a traditional lightweight race bike like the SuperSix EVO. For consistency this is assuming the same wheels on both bikes. The difference is in weight and aerodynamics; SuperSix EVO is 1 kg lighter* than SystemSix but suffers from 0.034 m^2 greater aerodynamic drag. *1 kg weight difference is for a rim brake SuperSix EVO as ridden by our professional athletes.

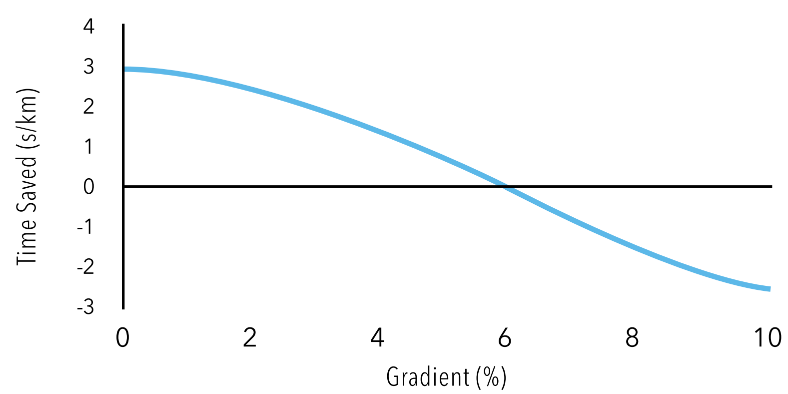


Figure 5 – The tipping point between a modern lightweight bike and SystemSix. Positive indicates time saved on SystemSix in s/km.

Figure 5 shows a time saving, in seconds per kilometer, for the SystemSix vs SuperSix EVO. The positive region indicates that SystemSix is faster than the modern lightweight race bike. The negative region is the reverse; the lighter bike has the upper hand. For example, at 0% gradient, SystemSix saves 3 s/km over SuperSix EVO, for this rider (4 W/kg). The horizontal intercept is the gradient at which the two bikes are equal in performance. In **Figure 5**, the break-even point occurs at 6%, This means that on a 6% slope, you would be equally fast on either bike. Only above 6% is there an advantage to riding the lighter weight bike. This means that on slopes less than 6% SystemSix,

despite a higher weight, is in fact, faster up hill. This is a new concept for a lot of cyclists. It is also one of the key reasons SystemSix offers more speed more of the time.

It is worth noting that 6% is quite a significant grade. Many of the grandest climbs in the European alps average a 7% grade. So when we consider SystemSix being faster on slopes up to 6%, it encompasses a very large chunk of the terrain covered by most riders.

This tipping point is affected by the mass and power of a rider. Higher power-to-weight ratio (for a stronger rider) shifts the tipping point to a higher gradient. This is because more power results in higher climbing speed and thus the influence of aerodynamics is more pronounced. For our professional riders that are climbing at and above 5 W/kg the tipping point is closer to 7%. This effect is shown in **Figure 6** below plotting tipping point against power-to-weight ratio. The key takeaway from this is the fact that it is actually possible to climb faster on a heavier bike than a light bike given sufficient aerodynamic improvement.

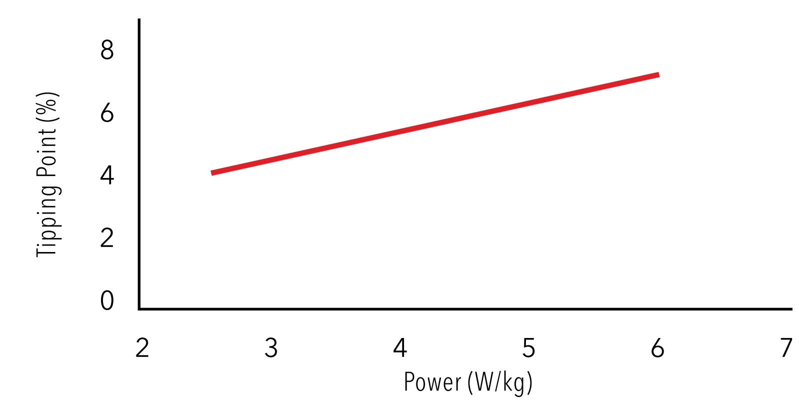


Figure 6 – Variation of tipping point with power-to-weight ratio.

This result is interesting when you consider the power distribution shown in **Figure 4** (page 8). You can see that at a gradient of 6%, the climbing power (PE term) is an order of magnitude bigger than the aerodynamic power. And yet, at 6% the performance is equal. The reason for this is because climbing power is a function of total mass. And for a bicycle, the rider has much greater mass than the bike. Even a very large mass saving on the bicycle is relatively small overall. By contrast, aerodynamic savings, even on just the bike, excluding rider contributions, can be a much larger portion of the total system and thus have a larger overall impact on performance.

The Place for Light Weight

For most riders, the majority of ride time will be spent on roads with gradients less than this 6% tipping point. And for those more limited times when the gradient exceeds 6% it is worth considering what you sacrifice you are really making. Consider our rider at 4 W/kg on a 10% grade. At that power they are travelling at a little more than 12 km/h. At this speed the heavier SystemSix requires 2.7 watts more power to match speed with the lighter bike. It is worth asking, will that extra power make enough difference on the steep climb or is there more to gain on the rest of the ride with the huge savings at lower gradients and higher speeds?

However, for some riders, like our GC contenders and climbers of EF Drapac p/b Cannondale, those >7% sections of big climbs might be the most important moment of the whole stage. When we work with these riders we look at their critical moment in the race. That point where they know they will be at and beyond their limit. This is where we need to optimize performance. For a big mountain stage with extended stretches above 7%, the lighter weight SuperSix EVO is an important weapon because those riders can't afford to give away anything. But for the rest of us not tackling HC passes on a daily basis, the gains of the SystemSix up to 6% offer a big boost in performance, more of the time.

Aerodynamics

SystemSix Aerodynamic Performance

Aerodynamics is clearly a critical element in the performance of road bicycles. SystemSix was designed to have class leading aerodynamic performance. A bold claim; one that we have proven through benchmarking our competitors.

Wind tunnel testing remains the most reliable method for accurately measuring aerodynamic drag. We tested SystemSix at the San Diego Low Speed Wind Tunnel (LSWT) against the fastest bikes currently available in the elite racing segment. Bicycles were tested as sold and specified by the manufacturer. The drag of each bicycle is plotted in **Figure 7** on next page. Data is plotted as C_DA, normalized from drag measurements taken at 30 mph. Error bars have been omitted from the graph for clarity. Uncertainty in C_DA is approximately ±0.0005m2. Full details of bicycle builds can be found in **Appendix F**.

For a brief introduction to the fundamentals of aerodynamic drag, units and C_DA refer to **Appendix B**.

It is apparent from the figure that SystemSix has consistently lower drag compared to existing class leading road racing bikes. The closest competitor on sale today to SystemSix in this test was the Trek Madone. Compared to the Madone, SystemSix has an almost consistent offset in drag across the yaw range. The one exception to this trend is the Cervelo S5 which has the lowest drag in test at 20 yaw angle. Only at this single point does any competitor present significantly lower drag than SystemSix. We will discuss in the following section how this impacts overall performance and the significance of yaw angle.

For comparison, **Figure 7** also includes a classic road bike, modeled here by our SuperSix EVO with the same matched wheelset. Differences would be far greater with a traditional shallow wheelset. This shows a big difference between bikes that have been optimized for aerodynamic performance, compared to modern lightweight designs with round tube sections. Even with an increased scale, SystemSix can be seen to have significantly lower drag than the current generation of low drag road bikes.

Obviously yaw angles are important, as we ride in varying wind conditions on the road. And as evidenced by **Figure 7**, aerodynamic performance can vary significantly with yaw. While SystemSix is consistently lower, other competitors have lines that intersect, making it difficult to analyze and pinpoint performance differences. To simplify the interpretation of this data and to incorporate the real-world effects of yaw angle, we at Cannondale use the method of Yaw Weighted Drag (Barry 2018).

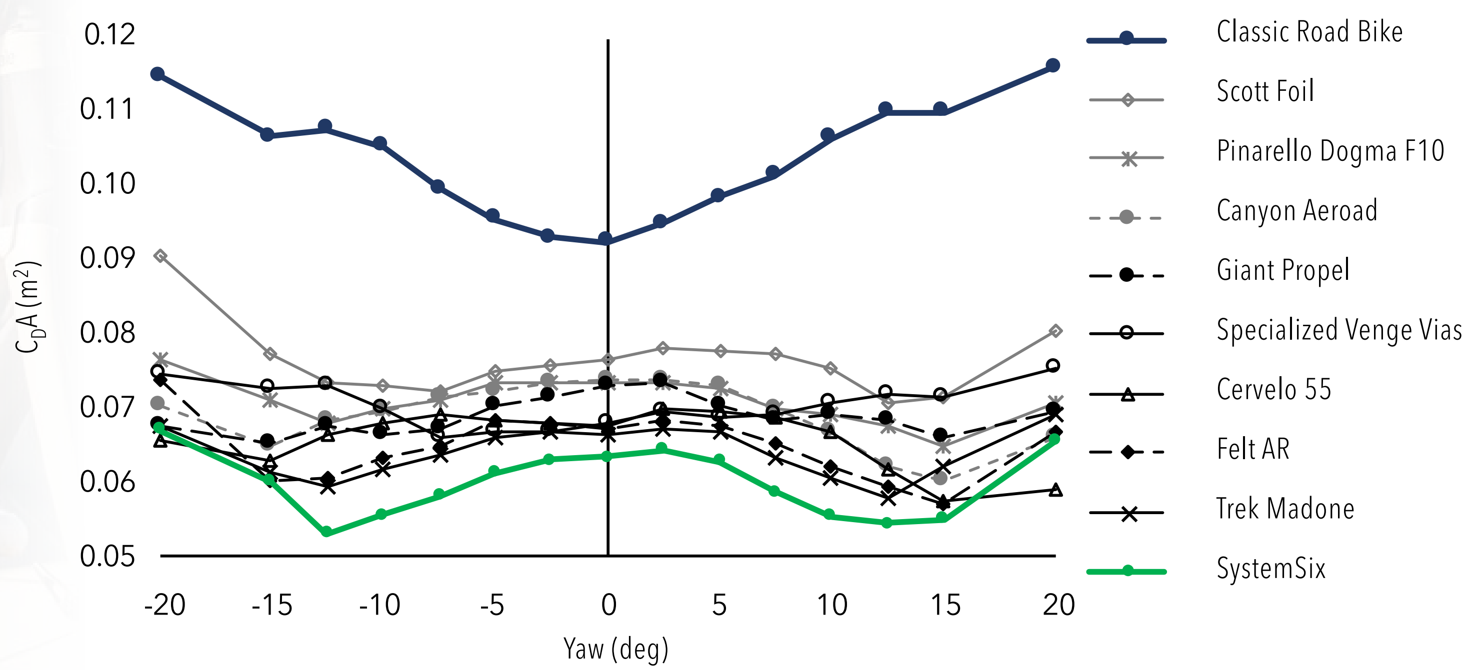


Figure 7 – Normalized drag (C_DA) vs yaw angle of competitor bikes compared to SystemSix.

Yaw Weighted Drag

The variation of drag with yaw angle makes it a difficult process to clearly state differences in aerodynamic drag, as seen in **Figure 7**. SystemSix consistently shows lower drag than competitors across the yaw range, but other curves intersect as drag varies with yaw angle. In assessing aerodynamic performance, we also need to consider that all yaw angles are not equal when riding on the road.

Yaw angles seen by a rider or vehicle on the road have been measured and discussed by various sources including: Cooper et al. 2003, Mavic, Trek, SwissSide, FLO Cycling. From this we know that low yaw angles are significantly more likely than high yaw angles with the distribution following a general Gaussian or bell curve. However, objectively combining the variation of drag with yaw angle with the probability of yaw angles is not agreed upon or widely communicated in cycling. At Cannondale, we use a method called Yaw Weighted Drag (Barry 2018). This methodology provides a statistical weighting function for yaw angle distribution that is used to weight drag measured in the wind tunnel. Taking the normalized integral of this weighted curve provides a single value called Yaw Weighted Drag and is denoted C_DA^*. Yaw Weighted Drag condenses all the information contained in **Figure 7** (on previous page) combined with the statistical likelihood of yaw angles on the road. This makes analysis of aerodynamics much simpler as we can now plot C_DA^* as a column chart (see **Figure 8**). A deeper discussion of Yaw Weighted Drag can be found in **Appendix D**.

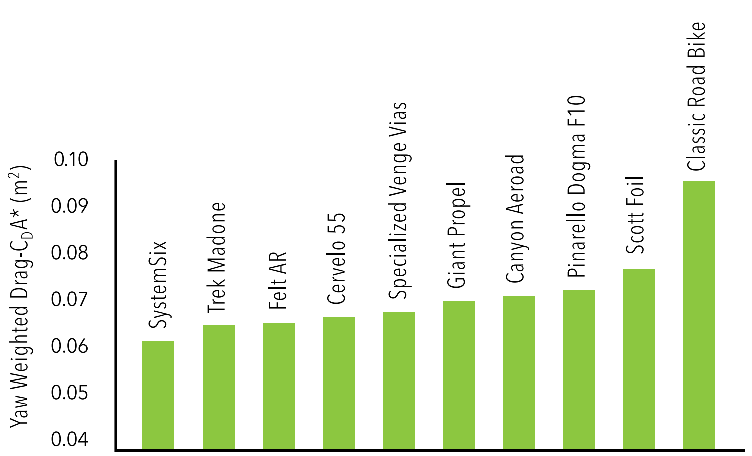


Figure 8 – Yaw weighted drag at 3.13 m/s wind speed, 40 km/h road speed.

Using yaw weighted drag, the comparison of aerodynamic performance can be greatly simplified. It is now obvious that SystemSix has the lowest drag of these high-performance race bikes. As a unit of C_DA^* it is not immediately apparent what this means in terms of on road performance; this will be addressed in more detail in the following sections. As a simple case we can look at the power required to overcome air resistance. **Figure 9** below shows the additional power required at 30 mph for each competitor bike compared to SystemSix. Where SystemSix is the reference; positive values indicate additional power required by that of the competitor. A modern road bike (SuperSix EVO) is included for reference.

Testing With and Without a Rider

Wind tunnel data in this report is presented for bicycles tested in isolation. This is the most controllable condition for testing of bicycles as it eliminates the instabilities introduced by a rider, even a mannequin. It does have its limitations, however, as testing without a rider does not capture the true flow field around a bicycle. It will be discussed later how SystemSix was developed and studied in simulations using a rider. However, it was not possible to replicate these conditions in the wind tunnel. This does not discount the wind tunnel results. Comparisons of testing and simulations show that the differences in drag from tests with and without a rider tend to be of similar magnitude. Sample tests were conducted with SystemSix against key competitors from above using a rider. While there is significant uncertainty in these results, they did confirm the trend seen in isolated bicycle testing as shown above and show that SystemSix has lower drag than its competitors.

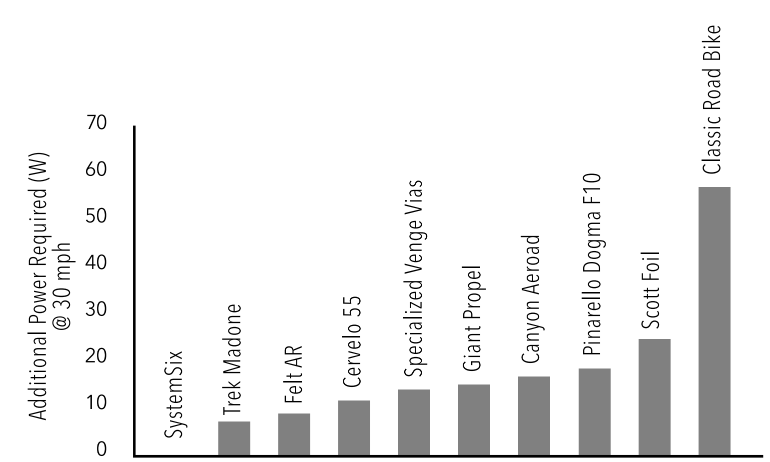


Figure 9 – Difference in yaw weighted air power at 30 mph relative to SystemSix. Positive values indicate additional power required above SystemSix from yaw weighted drag.

On Road Performance

While we can look at different individual metrics, the real measure of performance is what these elements add up to as a system on the road. This is how SystemSix was designed; to maximize speed on the road. We model this by taking the various performance elements and feeding them back into the power equation and simulate various riding scenarios. The three key performance metrics for a bike are: C_DA – aerodynamic performance, C_{RR} – tire rolling resistance and mass. We then add in the gradient of a given road.

From this point we can assess performance in two ways; either a power saving or a speed change. If we consider a fixed velocity, you can evaluate the difference in power with a change in setup or equipment. Or we can flip that around and use a fixed input power and look at how a rider's speed would change. From this you can then calculate a time saving over a given distance. This modeling process is where yaw weighted drag becomes critical because it provides a single value that can be used as the aerodynamic component in the power equation. We will now look at some typical riding scenarios that highlight the performance of SystemSix compared to a modern lightweight bike like SuperSix EVO.

Sprints

Sprints are an obvious scenario where aerodynamic optimization can have a big impact on performance. The high speeds of a finale mean that aerodynamic drag strongly dominates over other resistive forces. But just how much difference can aerodynamic savings makes during a final kick from the bunch? Let's compare SystemSix and SuperSix EVO – the two primary weapons of EF Education First Drapac p/b Cannondale. Consider the final kick with the final 200m covered at an average speed of 60 km/h. For a typical rider that 12s effort would require an average of 1000W. Over this final kick the SystemSix would achieve a 2.1 km/h top speed and reach the line 0.4 sec ahead of the modern race bike. That doesn't sound like a big margin, but at 60km/h that equates to 7.2m, or four bike lengths. That is a huge difference over just the final 200m of a race. Add to this the fact that SystemSix requires far less power on the high speed run in to the finish, even when drafting.

Breakaways

There are many different scenarios that we could consider when looking at a breakaway. The first is sitting in the wind, either breaking away solo or pulling on the front of the group. On a flat road at 45 km/h SystemSix saves over 40W compared to a modern race bike like SuperSix EVO. That is with the same deep race wheels on both bikes. That is a lot of energy if you are planning on going off the front for any length of time.

But what about drafting? This is an area of performance that is often ignored because in the peloton riders are typically riding well below their limit. But if you consider any racing condition, riders in the peloton want to conserve as much energy as possible, whether it is a breakaway where riders need to recover for their next turn at the front, a GC rider in a stage race conserving energy for key stages or a sprinter biding their time for the finale. Scientific literature has confirmed what we know from experience; drafting greatly reduces aerodynamic resistance. Riding in second position, this drag reduction is of the order of 40% (Zdravkovich et al. 1996, Barry et al. 2014) and potentially even greater when in a large group. This scaling also applies to any aerodynamic savings. That means a saving of 24W @ 45 km/h for SystemSix compared to a modern lightweight bike, even when drafting. That is a lot of energy to save over the course of a long day in the break, or even your local group ride.

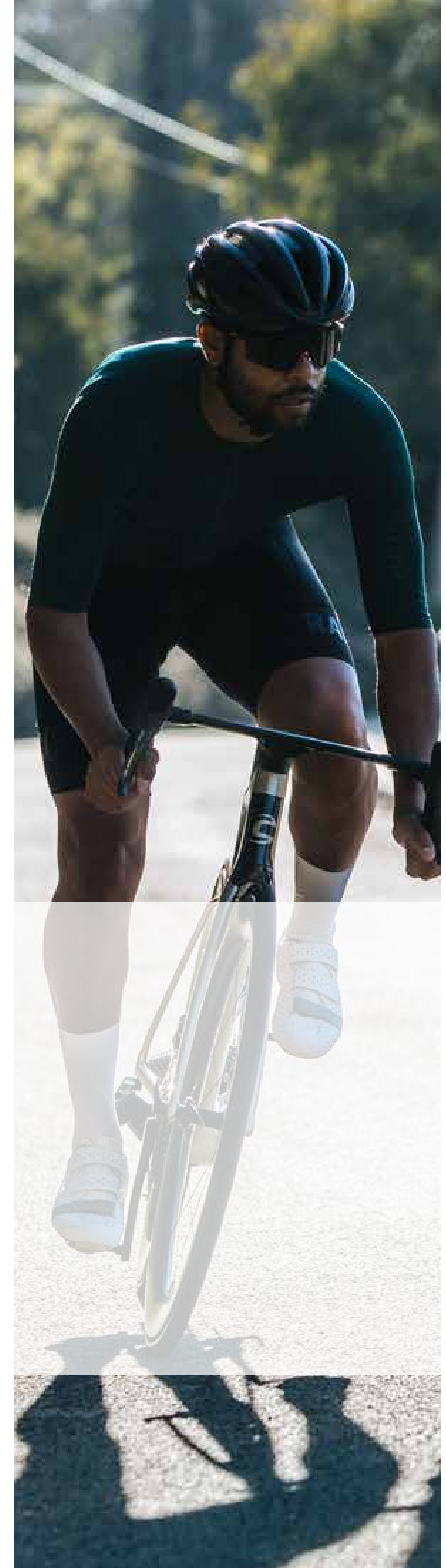
For a race scenario it is also important to consider what this performance can mean in terms of time saving. At race speeds SystemSix saves 3 s/km over the modern race bike. This savings adds up significantly over the course of a long breakaway. And it is really important when you consider the run in to the finish. Over the final 10km of a stage that time saving means SystemSix would get to the line 30 sec ahead of the modern lightweight race bike. For a rider off the front trying to fend off the charging peloton this could be the difference between winning and being swallowed up in the final kilometer.

Descending

Descending can be an equally important part of cycling. The high speeds mean that a lot of distance can be gained, or lost. We generally can consider descending performance under two conditions; rolling and pedaling.

First, consider a rolling descent. Aerodynamic drag is the key component in defining terminal velocity. A rider rolling down a 6% grade on SystemSix achieves a terminal velocity of 63.6 km/h (~40 mph). A rider on a modern lightweight bike requires nearly an additional 130W power output just to keep up. Now let's take a steeper descent where riders are completely spun out and just rolling. For an 8% non-technical descent with no braking, SystemSix tops out at 74 km/h. The rider on the modern lightweight bike is 5.4 km/h slower in this case. Over a 1 km section of decent this is a time difference of nearly 4 seconds or almost an 80m gap on the road.

Now let's consider a racing scenario with a pedaling descent. On a 5% grade at 200W, the rider on SystemSix achieves 61 km/h. To match that speed on a lightweight climbing bike the same rider would require 310W. This can be the difference between recovering on a descent versus pushing at the limit, just to keep pace.



Climbing

The tipping point, as discussed previously, is the gradient at which mass becomes more important than aerodynamics. This is a useful way to interpret climbing performance between two different setups, or bicycles. This gradient is then easily applied to any given road segment to assess time gain or loss. This was previously presented in "The Tipping Point" on page 10.

It is also worth putting numbers to how much power it requires to carry any additional weight on a climb. Consider the same rider used in the Tipping Point example riding either a SystemSix or a modern road bike like a SuperSix EVO. For a fixed 300W we can calculate the riders speed on the modern road bike. If we consider that same rider, riding the same speed on SystemSix, how much power do they save or lose depending on the gradient? We can answer this in **Figure 10** below. You can see that at low gradient and high speed that the savings from SystemSix is signifcant. Nearly 30W at 0% and 40 km/h. As gradient increases, approaching the tipping point, the savings reduce and then flip. Above the 6% tipping point the lighter bike has the advantage. But, as you can see, the savings are small. Even at 10% grade, the 1kg lighter bike saves less than 3W, compared to the 29W saving of SystemSix on a flat road.

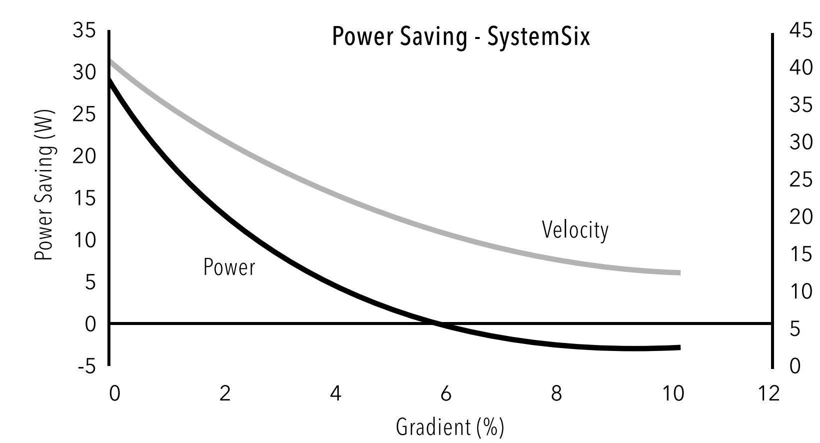


Figure 10 – Power saved riding SystemSix compared to a modern lightweight road bike. Speed calculated from typical rider values on the lightweight bike.

Not Just For Racing

Racing provides some clear examples of the performance benefits of SystemSix compared to a modern race bike over a range of different scenarios. But SystemSix is not just for elite racers and offers serious benefits to riders of all levels. Take a cruising speed of 30 km/h (~18 mph) on a flat road; a comfortable cruising speed for most road cyclists. Compared to a modern road bike with low profile wheels, SystemSix would save that rider approximately 17W just in aerodynamic resistance. This pace equates to a savings of about 10% of your total power. That is not an insignificant amount when you consider a training ride of several hours. And as you ramp this speed up for more spirited riding the savings only increases. At 32 km/h it's 20W. At 35 km/h it's 26W.

Acceleration

The analysis presented thus far has focused on steady state conditions; no acceleration. While many scenarios in cycling, both racing and training, can be well considered with negligible acceleration, this is not universally the case.

One of the key questions we get from those concerned with weight, is the effect on acceleration. This is a common criticism of deeper section wheels posed by climbers. If we consider the cycling power equation again we note that there is a term that accounts for acceleration in the form of changing kinetic energy.

$$P_{KE} = \frac{1}{2}\left(m_B + m_R + \frac{1}{r^2}\right) \frac{(V_{R2}^{\,2} - V_{R1}^{\,2})}{(t_2 - t_1)}$$

Consider accelerating from 20 km/h to 25 km/h in 2.5 s – a powerful acceleration of 2 m/s^2. This acceleration would require 280W for our reference rider. Note that this is independent of gradient. The gradient affects the potential energy term and so power required to overcome the gradient will increase with velocity; but that is independent of the acceleration itself. For example, on a 7% grade climb, riding at 25 km/h requires an additional 74W compared to riding at 20 km/h.

Acceleration, much like climbing, is a function of the total system mass. Thus, most of your energy is expended to accelerate your body mass, with the bicycle being secondary. A bicycle that weighs an extra 1 kg requires only an additional 3.5W additional power to perform that 2 m/s^2 acceleration. This is 1.3% increase in power. For a 75 kg rider and a 7 kg bike, a 1 kg mass increase is a little over 1% of the total system mass which is in proportion to the additional power.

When you consider the difference in mass for a wheelset, it becomes clear that it has little impact on acceleration. For a 100g increase in wheelset mass, at worst, only 0.7W additional power would be required for this acceleration. This accounts for both translational and rotational acceleration, and assumes all rotational mass is concentrated at the tire outer radius. Remember too that as you accelerate, your aerodynamic resistance climbs rapidly. From 20 km/h to 25 km/h your aerodynamic power doubles. So even for an acceleration on a climb, as modeled here, there is little to no advantage of a lightweight wheelset.

Deeper wheels do have some differing handling characteristics compared to their lighter, low profile siblings. Out of plane torque, both additional rim mass and aerodynamic resistance affects the roll of the bike; how the bike feels as you lean it over. Whilst this can feel different on a deeper wheel, this feeling is in the lateral plane of the bike. This has little to no effect on the forward motion of the bike, which is what dictates speed.

Weight

Whilst weight plays a secondary role to aerodynamics in most riding scenarios, there is no need to lug around more bike than you need. All things being equal, less weight is always a good thing. To minimize the weight of SystemSix without sacrificing stiffness, we used Hi-MOD carbon fiber as the primary material throughout the frame. This is one of the highest performing types of carbon fiber available, and the highest grade of carbon that Cannondale (and most of the cycling industry) has utilized to date. The use of such high-performance materials enables us to have larger surface area on the frame, for minimizing aerodynamic drag, without a significant weight penalty. **Figure 11** shows the bonded frame weight for SystemSix Hi-MOD. The bonded weight is the raw manufactured weight before paint and small parts. Small parts add up to 65g. Paint adds a further ~70g depending on the paint scheme.

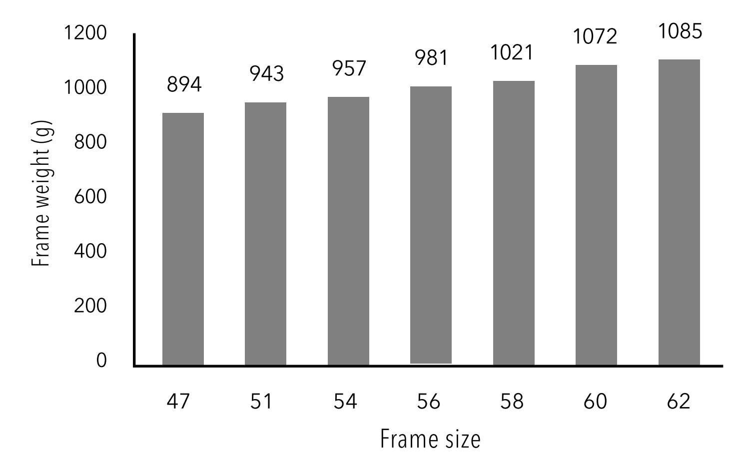


Figure 11 – Frame bonded weight for SystemSix Hi-MOD. Bonded weight does not include paint or small parts.

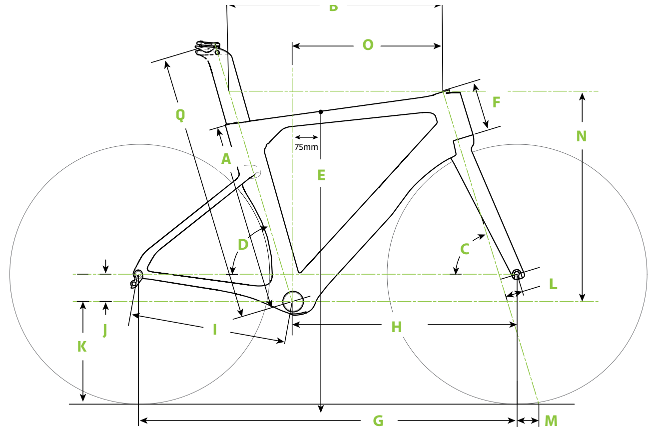
Handling and Ride Character

The responsiveness and handling of a bike are driven by geometry and stiffness. Any race bike from Cannondale needs to have that confidence inspiring steering response and stiffness that are trademarks of our SuperSix EVO and other models.

From inception, SystemSix was developed around the race proven steering geometry of our elite race platform. Two different fork offsets (45 and 55mm) are used to provide consistent feel and handling across the range and ensures that the ride experience for smaller riders is not compromised.

Geometry

SystemSix comes with our elite race stack and reach. This allows riders to adopt an aggressive long and low posture. However, with adjustable cockpit and spacers, SystemSix is for every day riders as much as it is for the racer.



	47	51	54	56	58	60	62
A SEAT TUBE LENGTH (CM)	38.5	43.3	48.2	53	55.3	57.7	60
B TOP TUBE HORIZONTAL (CM)	51.4	52.9	54.4	56	57.6	59.2	60.9
C HEAD TUBE ANGLE	71.2°	*	73.0°	*	*	72.9°	*
D SEAT TUBE ANGLE	75.1°	74.7°	74.3°	73.9°	73.5°	73.1°	72.7°
E STANDOVER (CM)	68	72.3	76.2	79.8	82.1	84.3	86.3
F HEAD TUBE LENGTH (CM)	8.8	11.4	12.8	14.9	17.2	19.3	21.4
G WHEELBASE (CM)	97.4	98.9	97.5	98.7	100	101.2	102.4
H FRONT CENTER (CM)	58.2	59.5	58.1	59.3	60.5	61.7	62.9
I CHAIN STAY LENGTH (CM)	40.5	*	*	*	*	*	*
J BOTTOM BRACKET DROP (CM)	7.9	7.4	7.2	*	6.9	*	*
K BOTTOM BRACKET HEIGHT (CM)	26.1	26.6	26.9	*	27.1	*	*
L FORK RAKE (CM)	5.5	*	4.5	*	*	*	*
M TRAIL (CM)	5.8	*	5.7	*	*	5.8	*
N STACK (CM)	50	52	54	56	58	60	62
O REACH (CM)	37.5	38.1	38.6	39.2	39.8	40.3	40.9

Figure 12 – Geometry chart.

Stiffness

The stiffness of a bike is important in the feel and responsiveness of the frame, both to steering inputs and putting the power down through the pedals. SystemSix was developed to match the head tube (HT) and bottom bracket (BB) stiffness benchmark set by our proven SuperSix EVO. Stiffness is optimized per size for ideal handling for all rider sizes. Taller riders, on average, are stronger and heavier than lighter riders, and the longer frame tubes of larger frames can often mean that larger frames are less still than small frames. Ideally HT stiffness should increase with frame size. **Figure 13** shows the frame stiffness across the size range of SystemSix. You can see that HT stiffness generally increases with frame size and sits above the ideal for all sizes. BB stiffness is constant across the size run, consistently exceeding our ideal target. Both Hi-MOD and carbon frames have the same stiffness. They are also geometrically identical. The only difference is the layup, which results in the slight weight increase of the carbon frame compared to the Hi-MOD (140g).

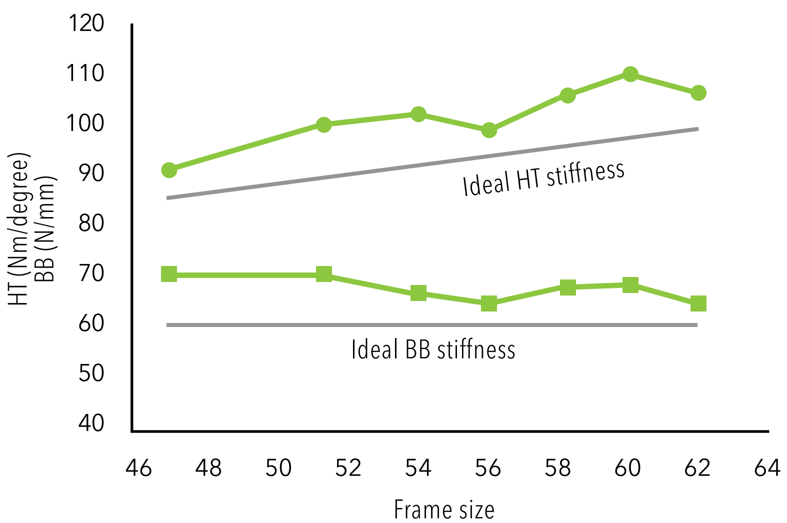


Figure 13 – Head tube (HT) and bottom bracket (BB) stiffness for all frame sizes of SystemSix.

Comfort and Ride Feel

Comfort and ride feel are an important element of any bicycle. In conceptualizing SystemSix we wanted to ensure that we could deliver the maximum gains in speed without sacrificing the feel of our modern race bikes. When we consider the comfort of a bicycle, we are really talking about compliance; the vertical stiffness.

The bicycle system is comprised of many components that connect the rider to the road; tires, wheels, frame, seat post and saddle. Each of these elements has their own stiffness that contributes to the overall stiffness of the bicycle system. Whilst the frame and fork can have an influence on this, for rigid frames, it is the tire that typically has the greatest impact on compliance. And we know that tire stiffness is driven by tire pressure. Herein lies the advantage of larger tires. Using a larger volume tire gives you more height which allows you to run lower pressures without bottoming out the rim.

In conceiving SystemSix this led us to create a bike that would have world leading aerodynamics with a larger tire than is traditionally found on race bikes. Many of the current generation of race bikes are still optimized around a small volume tire, especially when presenting wind tunnel data, where small tires outperform larger tires. We have seen this in our own testing and has also been reported by FLO Cycling amongst others. SystemSix bucks this trend by starting with a minimum 26mm measured tire. By using a larger tire a rider can run lower pressure for a more supple ride, improved road feel and comfort, without sacrificing any aerodynamic performance. We will look at the design details of the wheel in the coming sections.

For a detailed discussion of tire mechanics we recommend you take a look at the work of Silca; https://silca.cc/blogs/

SystemSix Details

There is little doubt of the important role that aerodynamics plays in the performance for all road cyclists, not just racers. With this knowledge reinforced, we set out to minimize the aerodynamic drag on all elements of the bike. By taking a holistic view of the bicycle system we came to incorporate the frame, fork, seat post, handlebar, stem and wheels. In developing SystemSix we broke the bike down into 3 aerodynamic zones:

1. Front wheel, fork, HT, DT, TT
2. ST, SP, BB
3. SS, CS, rear wheel

Aerodynamics were optimized using both computational fluid dynamics (CFD) and wind tunnel testing. These two techniques are complimentary and best results will always come when combining the two. CFD simulations in zone 2 and 3, and on full bike models, were conducted with a rider model on the bike to ensure a realistic flow field. This shows that some areas of the bike are heavily influenced by the presence of the rider such as the seat post. Wind tunnel testing was used to validate the design and to benchmark competitors as this is the most accurate measure of aerodynamic performance.

Figure 14 – Computational fluid dynamics (CFD) simulation of SystemSix with rider

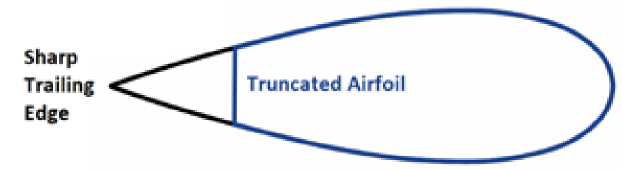


Figure 15 – Airfoil with sharp trailing edge (black) and truncated airfoil created from same airfoil (blue).

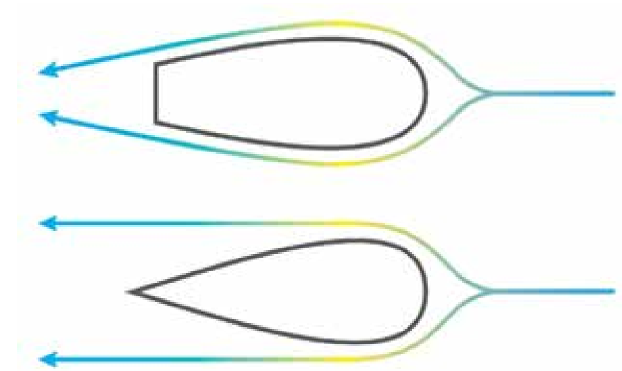


Figure 16 – (Top) Flow around a truncated airfoil with correct tail gradient with flow attachment along full length of body. (Bottom) Flow around a profile with too steep tail gradient leading to early flow separation.

Truncated airfoil sections can be seen throughout the SystemSix frame, fork, SP, and handlebar. A truncated airfoil simply refers to an airfoil section that has had a portion of the tail chopped off rather than finishing at a sharp trailing edge. However, the point at which the airfoil is truncated from the initial airfoil shape, means that truncated airfoils represent a large family of profiles with potentially very different aerodynamic properties. Each tube on SystemSix received a unique profile specifically selected for optimum performance in the local flow conditions.

It is worth noting that for attached airflow, a truncated airfoil will always have higher drag than a complete airfoil with a long tail. The low drag of an airfoil stems from minimizing the pressure drag that arises from a separated wake and resulting low pressure region behind the body. On an airfoil the tail allows the flow over the upper and lower surfaces to recombine with negligible wake. By truncating an airfoil, by definition, you remove this characteristic and introduce intended separation and thus a wake. However, by carefully designing the profile and the amount of truncation it is possible to minimize the increase in pressure drag but remove some of the length of the airfoil. When done correctly it is possible to introduce a small drag penalty but large reduction in perimeter, which saves weight.

SystemSix was designed to ensure that flow remained attached along the full length of the tubes and to maintain that attachment as late as possible in yaw. It has been shown that low yaw angles are always more prevalent than high yaw angles (Cooper 2003, Mavic, Trek, FLO, SwissSide) with the distribution generally following a Gaussian or bell curve. By keeping flow attached with a fixed separation point we minimize drag at the important low yaw angles, rather than focussing on high yaw and post stall performance, which has much less impact on overall performance. The critical parameter for flow attachment is the curvature of the tube beyond the point of maximum thickness. If the curvature, or gradient, of the tail is too sharp, the flow will separate in the adverse pressure gradient. Separated flow then leads to a large wake and large pressure drag on the body.

Frame & Fork

The specific tube shapes used on SystemSix are also dictated by the strict rules of the UCI. The critical one being the collection of 80mm boxes that dictate the maximum depth of the tubes. The UCI rule states that the main tubes of a bicycle must be no less than 25mm and no deeper than 80mm. To understand the implications, consider an airfoil which is a slender body. Typically an airfoil has a thickness that is < 30% of the length. For a 25mm wide tube this would make the length 83mm. This means that any true airfoil will need to be truncated in order to meet the UCI rules. When you consider larger tubes, like a head tube that needs to house bearings, then the required width of the airfoil is larger. This means the full length of that airfoil also increases dramatically. In order to preserve the gradient on the tail, you end up with a large truncation for such tubes, similar to what you see on the SystemSix head tube. It is this attention to the shape of individual regions on the SystemSix to ensure flow attachment that leads to the differences you see between frame elements.

The unique wide shape of the fork crown, head tube and down tube junction arises from our zoned design approach. The front of the bike was designed with the frame and fork as a single piece. It was only after we were satisfied with the performance were they separated into two separate pieces. To this end the whole fork crown region utilizes a continuous airfoil section across the fork, HT and DT. This ensures clean flow across the front of the bike rather than breaking it up between a disconnected fork and frame. This is also aided by the disc only design which removes a rim brake caliper from the fork crown that would normally disrupt the clean free stream flow that hits this part of the bike. Eliminating a rim brake caliper also allows riders to fit tires up to 30mm wide.

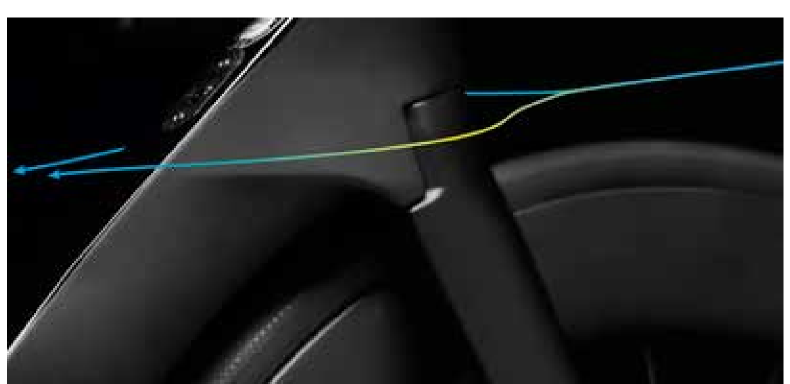


Figure 17 – A cross section of continuous airfoil over the fork crown.

The chine on the downtube is a unique characteristic of the SystemSix that serves a specific aerodynamic purpose. Due to the rake of the fork leg there is a pocket of flow that runs up the back of the fork leg towards the fork crown. The chine redirects this flow and channels it downstream, preventing it from continuing upwards and interfering with the clean flow over the fork crown and headtube above. Above the chine there is one continuous airfoil profile that encompasses the fork crown, head tube and down tube. This ensures clean flow over the entire fork crown region.

Figure 18– Flow moving up the fork crown is redirected downstream by the chine.

Creating a bike that could fully conceal brake lines was an important consideration during the SystemSix development process. We wanted to achieve a fully integrated system but with a design that was still easy for dealers and riders to service. From the outset we agreed that the brake lines would not pass through the head set bearings and that it should be possible to adjust stack without disconnecting any cables or hoses. The result is a design that routes cables through an enclosed channel in front of the head tube, bypassing headset bearings and the fork steerer. The head tube incorporates a separate carbon liner sleeve that protects the cables from contacting the steerer. The trade off to the ease-of-use design is that the steering angle needs to be limited so that excess steering angle cannot be applied and damage the brake hoses. Therefore, the steering on SystemSix is limited to ± 50°. Through extensive ride testing we determined that this is a far greater steering angle than is typically required when riding. In fact, you typically use less than 30° while riding as most steering is done through leaning. Only when performing low speed maneuvers or track standing will you ever feel the limit of the steering, even if you do notice it when wheeling the bike around.

Cockpit

The KNØT SystemBar and Stem is a unique setup designed specifically for SystemSix. It provides the integration of a one-piece bar and stem but retains the fit and adjustability of a two-piece system. The cockpit, especially the handlebar, has a profound impact on the drag of the bicycle system and so it is an important element of performance. However, a cockpit is central to fit and rider comfort on the bike. Herein lies the advantage of an integrated two-piece setup.

The KNØT SystemBar comes in four widths: 38, 40, 42 and 44cm. Every size bar has a 30mm flair from the hoods to the end of the drops. A size 42cm bar measures 40cm at the hoods and widens 30mm at the end of the drops (center-to-center). This narrower than standard hood position is designed to further help the rider maximise their speed. Narrower hand positions reduce frontal area and can help reduce drag on the rider, while maintaining width in the drops for stability when needed.

The bar and stem interface permits 8° of pitch adjustment in the handlebar. The bar tops use an airfoil section with a large truncation and gradual taper. This is relatively insensitive to pitch angle and ensures flow remains attached at all positions. Therefore, the drag penalty from personalizing your bar position is negligible. The bar cross section has large radii on the trailing edge for better ergonomics, but without sacrificing aerodynamic performance. If more comfort is desired then the bar tops can be wrapped with a relatively small aerodynamic penalty. Our wind tunnel testing showed that fully wrapping the bars, like a traditional round bar, only adds 0.001 m^2 drag; < 1W at 40 km/h (~25 mph).

The KNØT stem comes in a range of lengths to allow riders to dial in their fit: 80, 90, 100, 110 and 120mm. The stem is an open c-section design that cradles the handlebar and permits easy assembly. The lower cover then snaps into place once all the cables are in place. This is coupled with a split-hinge spacer design that allows a spacer to be added or removed without disconnecting hydraulic hoses or shift housing.

HollowGram KNØT64 Wheelset

The HollowGram KNØT64 wheel was the starting point for the entire SystemSix project. Since the front wheel is the leading edge of the whole bicycle it sees the cleanest airflow. Therefore, it was is an important starting point for aerodynamic optimization. The objective with the KNØT64 wheel was to design a wheel that would achieve low drag even when fitted with a minimum 26mm tire. Larger tires have many benefits for ride feel and comfort, but typically sacrifice aerodynamic performance.

When considering wheel aerodynamics, it is important to remember that the wheel and tire are a coupled system. For the leading half of the wheel, the tire is the leading edge and thus has a strong impact on the aerodynamic performance of the wheel. As the leading edge, the tire tends to control the separation from the leeside of the rim and thus drives the stall characteristics of the wheel. This not only affects the wheel but can be seen in the drag of the entire bike. When we consider a tire that is as wide, or wider than the rim, the flow tends to separate from the tire and is not able to reattach to the leeside of the rim in yawed flow. This leads to a wide wake and high pressure drag (see **Figure 19**). In contrast, the wide rim profile of the KNØT64 allows the flow from a wider tire to reattach to the rim cleanly and thus reduce drag.

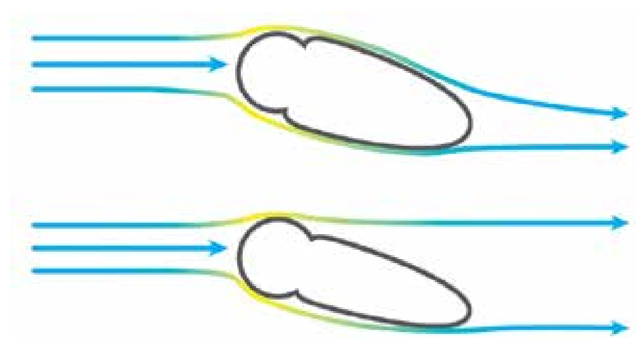


Figure 19 - (Top) Flow profile around the KNØT64 rim with its extra wide rim profile. Flow remains attached to the leeside of the rim at yaw, even with a wide tire. (Bottom) Flow around a wheel where rim and tire are of equivalent width. Flow separates from tire without reattaching to rim leading to wider wake and higher drag.

For this reason, many race bikes and wheels are still tested in wind tunnels with small tires. However, it is not widely reported what is sacrificed in performance when replaced with larger rubber. From the outset, we started with a large tire and designed a rim around a larger profile that could still meet our strict aerodynamic performance requirements. The result is a unique rim profile with an outer width of 32mm. This was only possible by committing to a disc brake only platform for both the SystemSix and the KNØT64 wheel. As well as being wide on the outside, it is also wide on the inside at 21mm. This means that tires grow to much larger than their named size when mounted on this rim. For example, a 23C Vittoria Rubino Pro Speed tire measures ~26mm* on the KNØT64 rim. The 25C version of the same tire measures ~28mm. That's a big tire on a race bike. And the shape of the rim means that you can run a 28mm tire with minimal increase in drag compared to a smaller 26mm tire.

To optimize performance of the wheel system (rim + tire) we have licensed technology from HED to spec the fastest possible tire. HED Cycling Products, Inc. Patent US8888195 B1 allows a wheel designer to predict and design in a particular stall angle to a wheel based on the tangent angle between the rim edge and tire, and having a fast wheel at the desired yaw angle(s).

The KNØT64 wheelset also includes a bespoke front hub with a smaller hub shell to minimize frontal area. At only 23mm diameter the hub is significantly smaller than many contemporary disc brake wheelsets.

HollowGram KNØT64 Wheelset	
Rim Max Outer Width	32 mm
Rim Bead Width	21 mm
Spoke Count (F/R)	20/24
Weight (F/R)	765/877 g

*Manufacturing variation means that actual tire size can vary between individual samples of the same tire model.

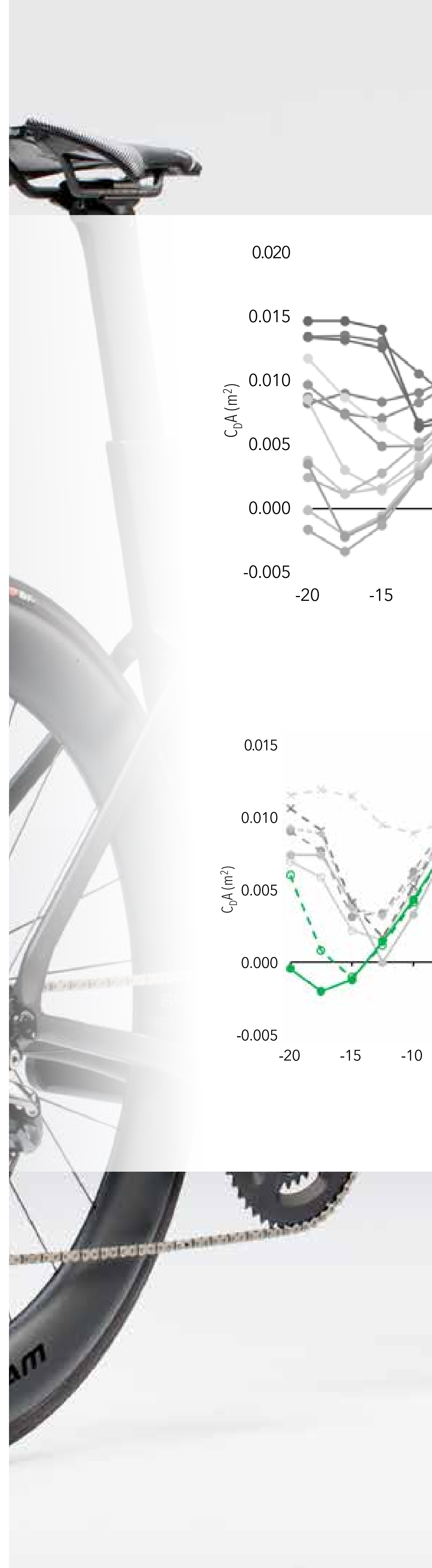
KNØT64 Aerodynamics

Effect of Tires on Wheel Performance

Tires have a profound influence on the drag of a wheel. **Figure 20** shows the KNØT64 rim tested with a range of different tires, all similar width. Drag at low yaw is tightly grouped with only small differences between tires. But at higher yaw angles the effect of tires on stall is pronounced; note the magnitude of difference at 15° yaw angle. The stall of the wheel is not only connected with the width of the tire but also the construction method and tread profile. The fact that the biggest differences occur at high yaw angles also highlights the value of yaw weighted drag in evaluating on road performance.

Our approach to wheels and tires is consistent with the whole SystemSix project; focused on speed. As we identified earlier, performance is not just about aerodynamics. This is especially true for wheels and tires as we must consider both the aerodynamic performance and the rolling resistance of a tire. A tire that tests well in the wind tunnel may have high rolling resistance that nullifies any aerodynamic benefit. Similarly, a low rolling resistance tire might be compromised by poor aerodynamics. We analyze performance using the power model taking yaw weighted drag from the wind tunnel and combining with the rolling resistance of each tire to model on road power differences. From this we can then determine the fastest combination. There are several public sources for rolling resistance data available, including conducting your own testing at home. We find bicyclerollingresistance.com a great resource for comparing the performance of a large range of road tires.

SystemSix comes with Vittoria Rubino Pro Speed tires which were selected due to their balance of low drag and low rolling resistance. The Corsa G+ is another high-performance tire from Vittoria but is hand-made, whereas the Rubino is vulcanised. The two tires are manufactured from identical compounds which leads to very similar rolling resistance. However, handmade tires like the Corsa generally have a significant aerodynamic penalty. Overall performance therefore favors the Rubino Pro Speed. Just another area where SystemSix delivers more speed to more riders.



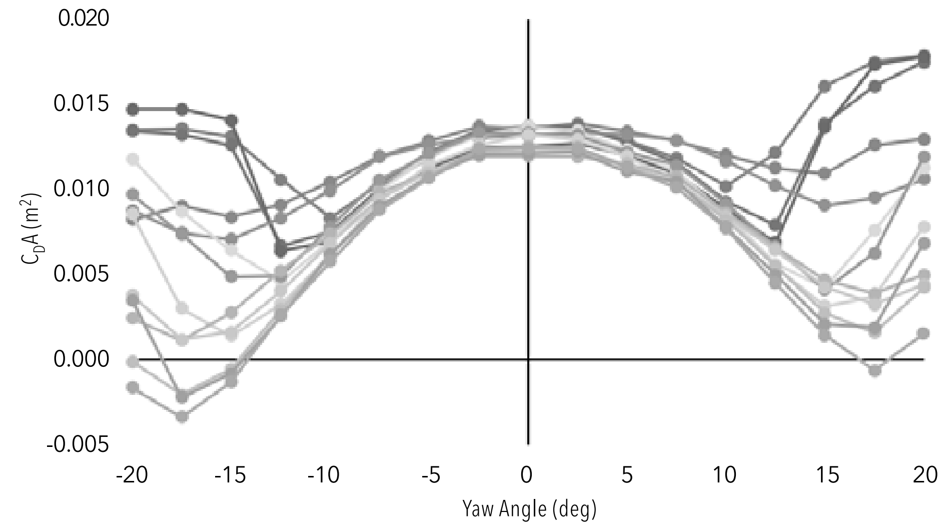


Figure 20 – KNØT64 rim tested with a range of different tires.

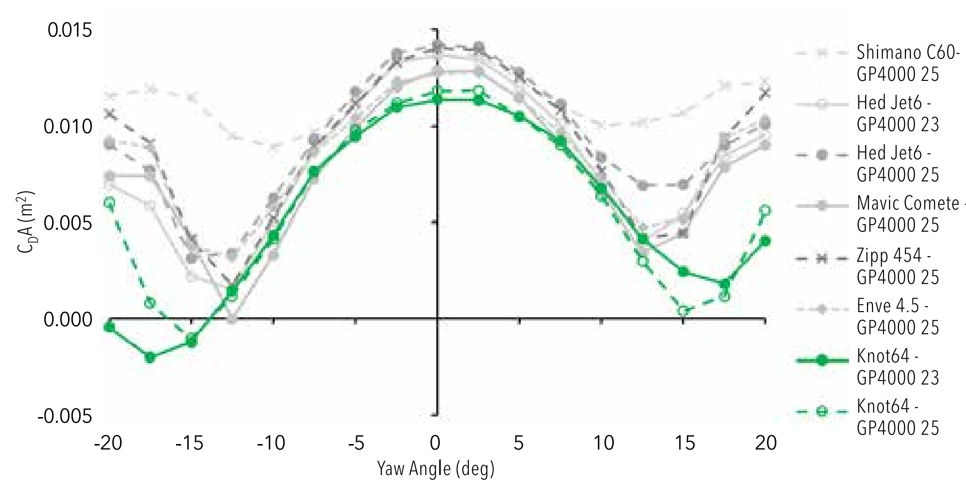


Figure 21 – Normalized drag (C_DA) of KNØT64 wheel and competitors.

Wheel Performance Against Competitors

The HollowGram KNØT64 wheels were tested at the San Diego Low Speed Wind Tunnel (LSWT) against a selection of high performance road wheels. As discussed previously, tires have a profound impact on the aerodynamic performance of a wheel. To normalize the test all wheels were tested with Continental Grand Prix 4000S II tires. Tires were chosen based on measured size, rather than named size, as variation in rim bead width greatly affects the physical size of the tire on the rim. And for a given tire, the width is the important variable to normalize, rather than the labeled size. The normalized drag (C_DA) vs yaw angle are plotted in **Figure 21**. All competitor wheels were rim brake configuration. Disc brake wheels are generally considered to have performance secondary to rim brakes. To avoid any bias towards the KNØT64 being disc brake only we selected competitors high-performance rim brake wheels. The Hed Jet was tested with both 23C and 25C tires as it has the same wide 21mm internal width as the KNØT64.

In this form the results are somewhat difficult to interpret as the intersecting lines make it unclear which has the best aerodynamic performance. **Figure 22** below shows the yaw weighted drag of each wheel in this test to simplify the analysis and eliminate the ambiguity of variation with yaw. Note that the 25C has only marginally higher drag than the 23C tire. On the KNØT64 this 25C tire measures 28mm, showing that you can run large tires with minimal sacrifice in performance.

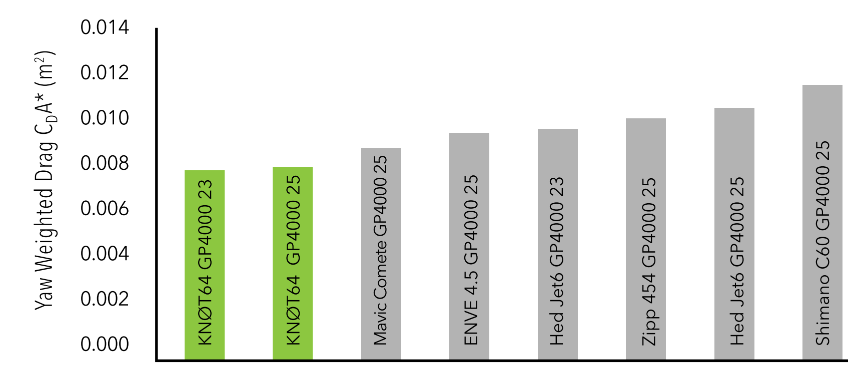


Figure 22 – Yaw Weighted Drag (C_DA^*) of KNØT64 wheel and competitors. Wind speed 3.13 m/s, road speed 25 mph.

Wheel Testing

At this point the more critical reader would ask; how does testing a wheel in isolation relate to performance on the bike? This is a very good question. On the bike the leading half of the rim may see clean flow, but even the back half of the front wheel is surrounded by fork legs, the down tube and even the rider's feet. The rear wheel is in the wake of nearly every other element. So does wheel testing in isolation provide us with useful information? Yes.

The data on the previous page shows that drag, in particular the stall point, is strongly influenced by the tire. This is driven by the separation of the flow from the wheel and tire. In practice, the wheel and tire are a system and their performance is closely linked. The wrong tire can ruin the performance of the best wheel; for example, using a tire that is far too big. The leading edge of the wheel, and indeed the whole bike, is the tire. The interaction between the wheel and tire dictates whether the flow can reattach to the rim after separating from the tire. This drives the stall point observed in the drag plot and correlates strongly with the stall characteristic of the entire bicycle. Since the leading half of the wheel, where this phenomenon occurs sees such clean flow, wheel performance on a bike correlates well to the results of isolated wheel testing.

Seat Post

The SystemSix seat post features a unique cross section matched to its local flow conditions to ensure flow attachment and to minimize drag. This follows the design of the rest of the bike, utilizing an airfoil section with a truncated tail. The seat post is an important contributor to the drag of the bike as it is an exposed element, despite being well downstream of the leading edge, and even with the presence of a rider. In fact, the legs of a rider accelerate the flow over the seat post to be greater than the road speed of the bike. Higher local velocity means that the drag force is also higher; recall the equation of aerodynamic drag (see **Appendix B**). The rider's legs in proximity to the seat post create a contraction that accelerates the flow between the legs and then over the seat post. In this case, testing without a rider reduces the relative contribution of the seat post as it would see flow at freestream velocity, not faster. This can be demonstrated by looking at velocity planes in CFD. **Figure 23** shows a color contour of velocity on a horizontal plane through the seat post. White regions are freestream velocity – the speed of the air around the bike. Yellow regions indicate flow faster than freestream, blue indicates regions where the flow speed is below freestream.

The presence of a rider's legs also introduces local yaw angles, depending on instantaneous position. This means that the post can see local yaw angles differing to that of the bike and rider system. The highly truncated airfoil profile and very gradual taper ratio ensure that flow remains attached even in the presence of these induced local yaw angles.

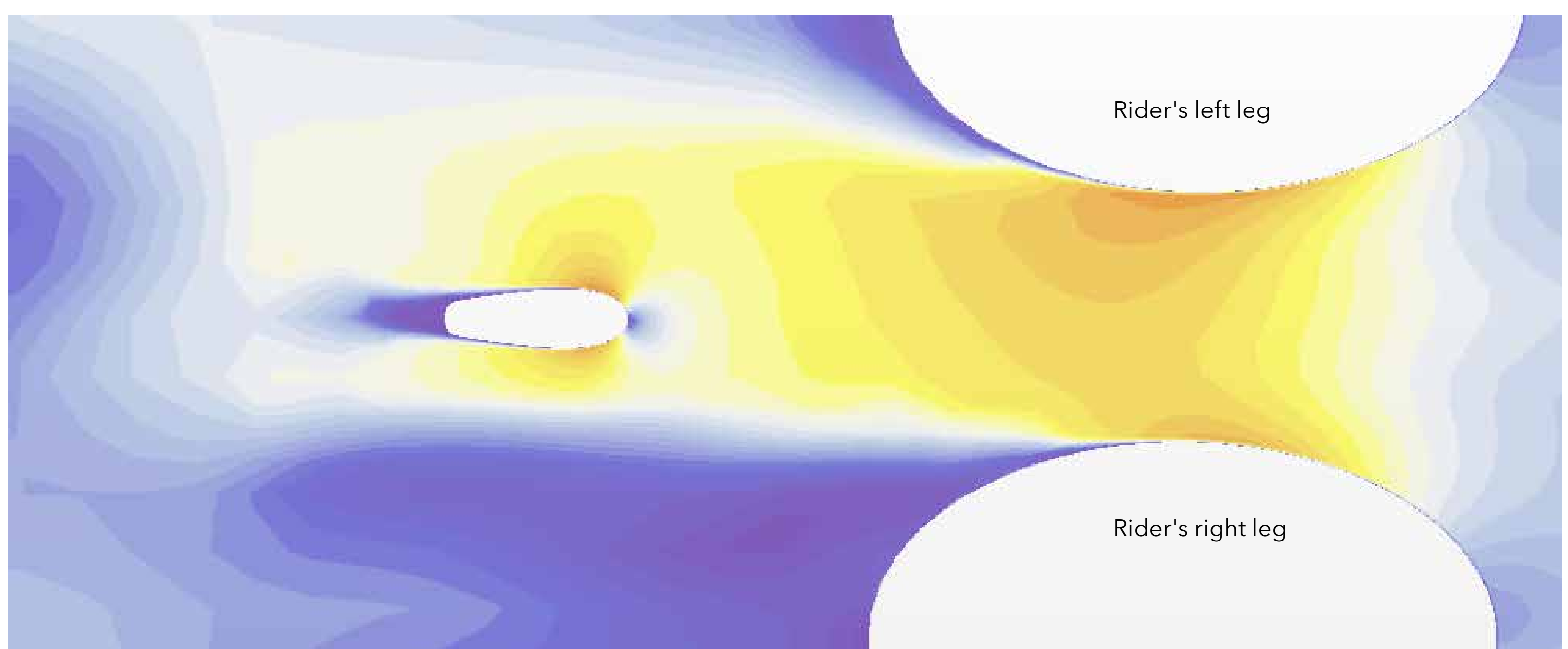


Figure 23 – Horizontal plane of velocity contour from computational fluid dynamics showing the accelerated flow between the rider's legs and over the seat post. Yellow/orange regions indicate flow velocity above freestream whereas blue indicates below freestream.

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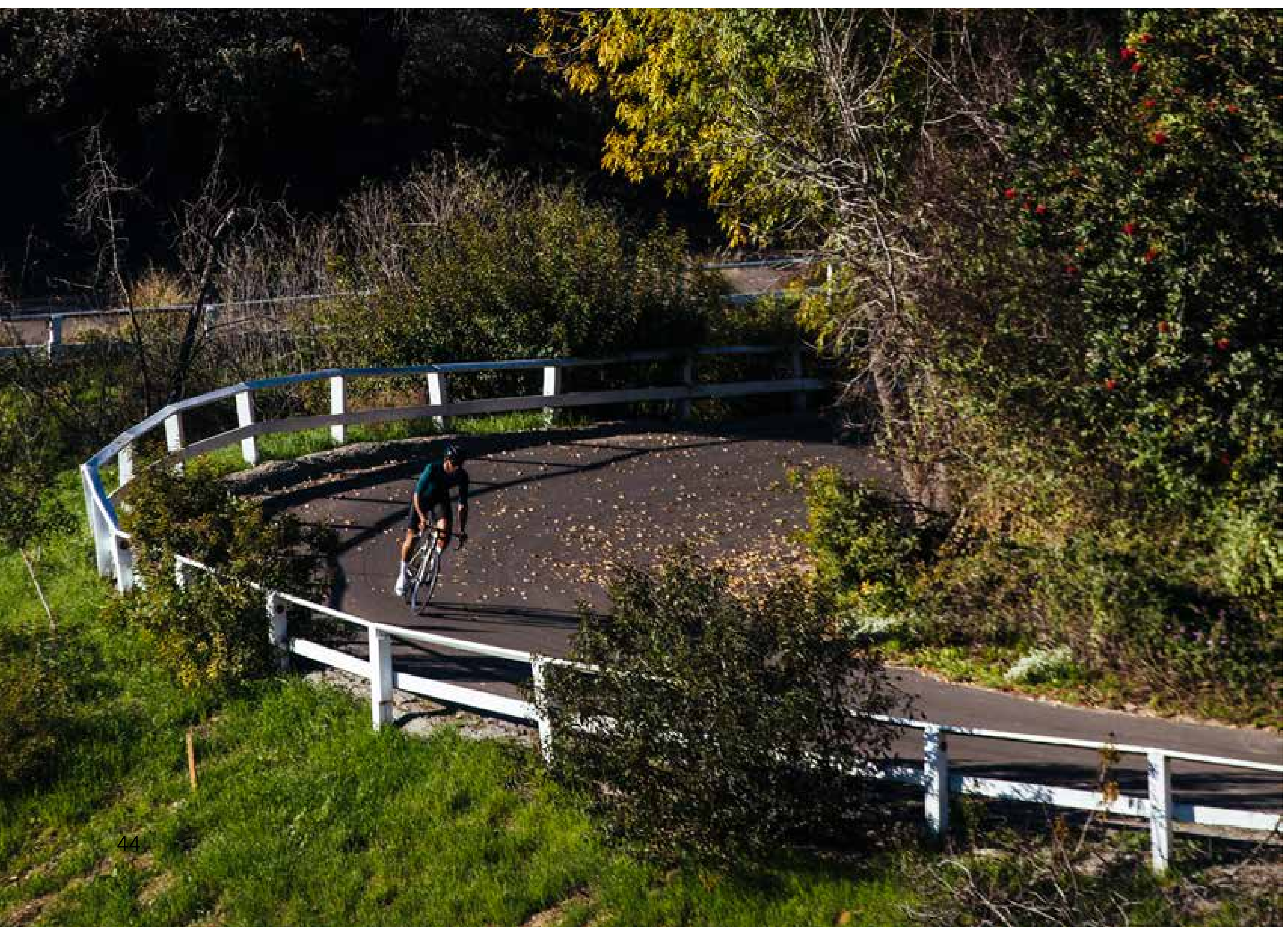
Glossary

$P_{Athlete}$	Input power from the rider.
P_{NET}	Net power.
P_{Aero}	Power due to aerodynamic drag.
P_{RR}	Power due to rolling resistance.
P_{WB}	Power due to wheel bearing friction.
P_{PE}	Power due to potential energy gain. This is the power it takes to climb a hill.
P_{KE}	Power due to kinetic energy. This is the power it takes to accelerate.
C_DA	The product of the coefficient of drag (CD) and the frontal area (A). This is a normalized form of drag removing the fluid dependent properties.
ρ	Air density.
V_A	Air velocity.
V_R	Road velocity.
μ	Coefficient of rolling resistance of tyres.
m_B	Bike mass.
m_R	Rider mass.
g	Gravitational acceleration.
G	Gradient.
η	Mechanical efficiency (%).
Chord	The length of an airfoil from its leading edge to the trailing edge.
Flare	For handlebars; describes the increase in width from the hoods to the end of the drops.
Frontal Area	The silhouette area of on object when viewed from the front. Commonly used as a reference area in aerodynamics.
Leeside	The surface of a body that faces downstream as opposed to the windward side which faces upstream.
Yaw Angle	The angle between the resultant air vector and direction of travel. Different from the wind angle due to the vector sum of wind and road velocity.

Appendices

Appendix A: Reference Rider Values

Rider Power	300W
Rider Mass	75 kg
Coefficient of Rolling Resistance	0.003
Air Density	1.2 kg.m-3
Mechanical Efficiency	97%



Appendix B: Introduction to Aerodynamic Units

For those familiar with aerodynamic data, you may have seen it presented in various units by the cycling community. It is regularly discussed in terms of grams, watts or a time saving. These are all derived from the same root in aerodynamic drag, but the units themselves can be misleading depending on how they are presented.

Aerodynamic drag is the resulting resistive force that acts on a body as it moves through the air. Grams is a unit of mass, not force. Grams is simply derived by normalizing the drag force by gravitational acceleration and converting units. Note that grams is not even a standard SI unit. Instead, it should be kilograms. Grams has been used in the cycling industry to date for 2 reasons. Firstly, mass units are easier to understand for those without an engineering background. And, secondly, because it typically results in a nice number. That is why we see grams rather than kilograms. However, this can be misleading because whilst it is the same unit as mass, the magnitude is much smaller than the mass of the system and yet can have a far greater impact on performance.

Power is another commonly referenced unit for aerodynamics. This has obvious relevance to cycling as many riders are familiar with it from training, especially with the proliferation of power meters in recent years. The issue with power, like mass and even force, is that they all scale with velocity. See the equation for aerodynamic drag below. Where C_D is the non-dimensional coefficient of drag, A is the frontal area, ρ is the air density and V is velocity.

$$Drag = C_D A \tfrac{1}{2} \rho V^2$$

Power is related drag as it is the product of force and velocity. Multiplying the aerodynamic drag by velocity (to give V^3) gives the aerodynamic power in watts. From this equation it becomes obvious that mass or power units of aerodynamic drag will depend on the reference speed. For this reason it is general practice in fluid mechanics and aerodynamics to normalize the drag force by dynamic pressure in order to get C_DA. This is then a unique term describing the aerodynamics of the body, and no longer a function of the fluid. In practice C_DA is not a constant, as it too can vary with wind speed. However, over typical bicycle ranges the variation in C_DA is much smaller than the velocity effects. In addition, the relative shift in C_DA tends to be consistent across different bicycles, so the data remains comparable. We measure C_DA at a speed of 30 mph (48.3 km/h) in the wind tunnel, the defacto standard for the cycling industry, and then use this to calculate performance at speeds by treating C_DA as a constant. At Cannondale, whenever we present an aerodynamic saving in terms of power it will always be accompanied by the velocity at which is was calculated in order to avoid ambiguity. When we analyze wind tunnel data we refer to C_DA as best practice for aerodynamics. This is how you will see aerodynamic data analyzed throughout this report.

Appendix C: Yaw Angle

Yaw angles are an important concept for ground vehicle aerodynamics. It is the angle between the direction of travel and the resultant air vector. This arises from the vector sum of the road velocity and wind velocity. As this is a vector sum, there is also an angular component. The yaw angle therefore is a function of wind speed, wind direction and road speed. The distinction between wind direction and yaw angle is important. Because a vehicle has a component of road speed, the yaw angle is always less than the wind angle. Typically, road speed is significantly higher than wind speed and it is for this reason that yaw angles tend to be much smaller than the wind angle. The wind vectors are depicted in **Figure A1** below.

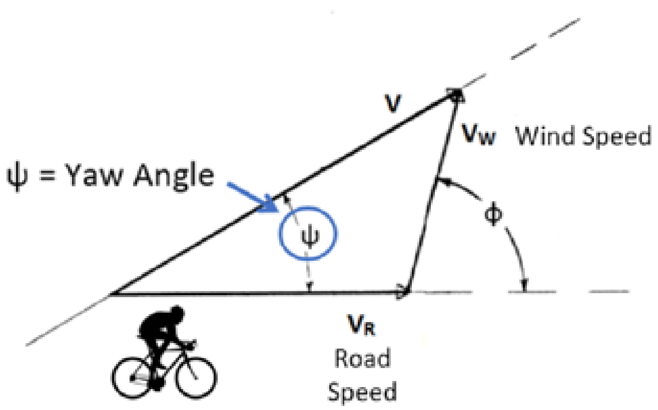


Figure A1 – Vector addition of velocity components defining yaw angle.

Appendix D: Yaw Weighted Drag

Aerodynamic drag is a key determinant in cycling performance. The distribution of yaw angles that a cyclist sees is equally as important as drag varies as a function of yaw angle. Yaw Weighted Drag is an objective method for combining aerodynamic drag, as a function of yaw angle, with the statistical likelihood of riders experiencing a given yaw angle. This method provides a simplified and intuitive approach to condense the analysis of aerodynamic performance and yaw angle.

The foundations of this lie in the generation of a statistical distribution of yaw angles seen by a cyclist. Yaw angle is a function of wind speed, wind direction and road speed. This is simple in concept, but in practice these parameters all vary greatly depending on time of day, season, weather and geographic location. This makes it a huge parameter space to try and measure experimentally. By deriving the yaw distribution analytically, it is possible to arrive at, what is effectively, a general solution for yaw angles on the road.

In the paper (Barry 2018) a general case is proposed using 7 mph (11 km/h) mean wind speed and a road speed of 25 mph (40 km/h). This wind speed is derived from experimental measurements and is consistent with automotive industry practice. A road speed of 25 mph represents a balance between racing speeds and general riding speeds. Full details of the derivation can be seen in the paper.

The probability distribution of yaw angle is then used to transform the experimental aerodynamic data from wind tunnel tests. Normalizing the probability function and then scaling the wind tunnel data accordingly creates a new plot where the magnitude of drag is proportional to the statistical likelihood of a rider experiencing that yaw angle. To condense this data into something more accessible we then take the normalized integral of the weighted drag curve. This results in a single unit, termed Yaw Weighted Drag (C_DA^*). This single number now encompasses the variation in drag across the yaw spectrum as well as the probability of experiencing those yaw angles. This makes comparing aerodynamic performance much more straightforward as you are now only comparing a single value and not a series of curves.

The normalized weighting values, along with full details of this method are provided in the paper. You can take this data and apply it to any existing wind tunnel data set to re-evaluate data with the added consideration of yaw angle.

Appendix E: Coordinate Systems and Airfoils

As a simple analogy, a vehicle in the airstream is similar to a wing airfoil. However, there is one key difference; the reference coordinate systems. For bicycles and vehicles, drag is the force parallel to the direction of travel, with side force perpendicular to this. For an airfoil or wing, the drag force is parallel to the wind vector, with the lift vector perpendicular. This is depicted in **Figure A2** and **Figure A3** below. For an airfoil, lift and drag are the decoupling of components from the resultant force vector. If you compare the two coordinate systems you can see that the two drag vectors are not parallel. If you consider a bicycle, or an individual airfoil element, the airfoil coordinate system results in the airfoil lift vector having a forward component that offsets the vehicle drag. Therefore, bicycles or wheels with deep airfoil sections experience larger side force than shallow or round tubes. As well as being more streamlined, at yaw there is the airfoil lift force, which decreases drag but also increases side force. By contrast, the round tubes do not have the same phenomenon at yaw and so have much higher drag, but also lower side force.

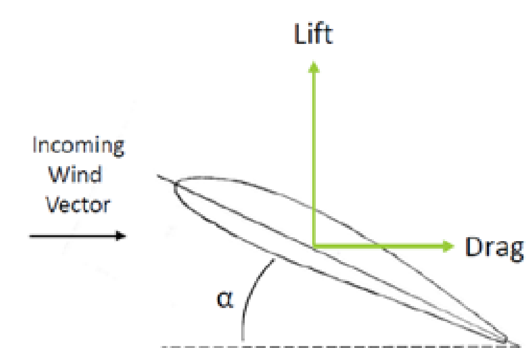


Figure A2 – Airfoil lift and drag.

This effect is felt on wheels. In strong cross winds it is easy to feel the difference in side force between a shallow wheel and a deep wheel. The deep wheel is faster, but there is an increased side force component that riders must control. For a given depth tube or wheel it is possible to tune performance to produce less side force for the same low drag, in the same way that airfoils differ in their lift to drag ratio. However, as a general rule, depth is a bigger driver. A 60mm deep wheel will generally have significantly higher side force than a shallower 40mm wheel, but also have much greater potential to reduce drag. Side force does not directly impact speed in the way that drag does. However, there is a point at which the side force can become too much for the rider to control and then compromises their ability to handle the bike. This is then a negative impact on performance.

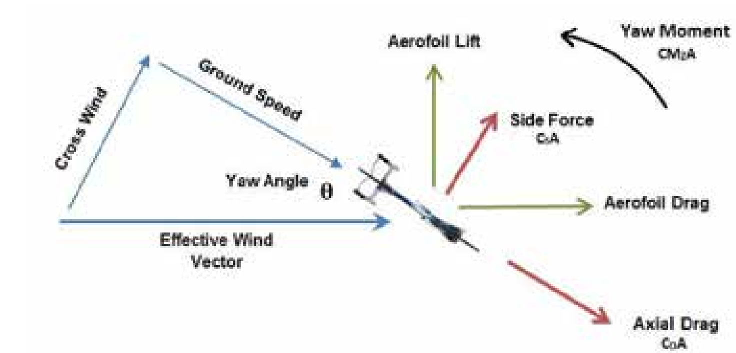


Figure A3 – Bicycle coordinate system. Note that vehicle axis drag differs from airfoil (or wind axis) drag.

Cross Wind Stability

Stability in cross winds can be an important aspect of riding performance. If the rider is no longer able to predictably control their bike then they can't ride efficiently. But what do we mean when we refer to "cross wind stability"? There are in fact multiple elements that all influence the way a bike reacts in strong cross winds. Three separate phenomena that can each affect how a bike handles in strong cross winds are:

1. Magnitude of side force
2. Sensitivity to gusts
3. Pulsing loads

The first is the magnitude of the side load acting on the bike. This is described in the section on the previous page. Side force is an inevitable result of yaw angles. However, deep section frames and wheels can experience higher side loads than shallow or round tubes. But a constant side force is not such a problem for handling. A constant force can be accounted for, typically by leaning the bike slightly. You would have instinctively felt this if you have ever ridden in a very strong cross wind. This lean counteracts the roll moment induced by the side force from the wind. But a constant load does have a strong negative impact as you can predictably correct for it. The real concern is fluctuations in side force. This occurs when there is a gust of wind. This leads on to the second effect; the gradient of the side force curve.

From a force perspective a gust of wind results in a sudden increase in yaw angle. Recall that yaw angle is a function of wind speed, direction and road speed. A gust of wind is a sudden increase in wind speed; this alters the vector sum and causes a spike in yaw angle. Now consider what that does to the forces on a bicycle. In drag, a burst of yaw will change drag, but this is an axial force. It may increase resistance, but as an axial force, it does not affect handling. Side force on the other hand, will affect handling. Side force on wheels is generally a linear function of yaw angle. This is true of most wheels (Barry et al. 2012). A sudden change in yaw can be modeled by moving along this graph. Since it is mostly linear we can see that an increase in yaw from a gust will result in a burst of side force. The desirable quality then is to have a shallow side force curve. However, the gradient of this curve is dominated largely by wheel depth. Altering depth, more than wheel type or design, affects the sensitivity to gusts.

It is worth noting that the handling of a wheel or bike in strong cross winds, and gusts, is a personal response. Larger riders, for example, are less susceptible to cross winds. When riding in cross winds we lean into the wind to offset the roll moment. A taller rider has a higher center of gravity and typically more mass. This means the lean angle required for a given roll moment induced by the wind, will be smaller than for a short, lightweight rider. On top of physical factors is that handling can be learned. Practicing riding on your deep race wheels will allow you to learn how they respond in strong winds and tune your handling skills accordingly.

The final element that is mentioned when discussing cross wind stability is the fluctuations in side force due to shedding. This is a complicated phenomenon that bares some explanation. When air separates from a body it is not necessarily a steady process. It can have a natural oscillation due to instabilities. This variation in the way the air separates from a body can result in fluctuations in force on the body, due to changing pressure drag. It is for this reason that you see helical strakes on car antenna or chimney stacks. These strakes actually break down this vortex shedding and reduce the stresses on the body. The mechanism by which this occurs is that the shedding frequency is increased, thereby redistributing the energy over lots of small pulses, rather than a small number of very strong pulses. You can imagine how this applies to bicycle wheels. If you had a strong pulsing force on you front wheel or fork then it could unsettle your handling. However, it is important to remember that this effect is separate from gusts. This pulsing in force stems from an aerodynamic instability and thus occurs in a constant cross wind. There is little experimental data available on such effects but experience suggests that any pulsing loads on a bicycle due to vortex shedding are so low in magnitude that they are largely unnoticed. It is really the gust sensitivity that is most noticeable as a cyclist.

Appendix F: Wind Tunnel Bike Specifications

	Wheels	Tires	Handlebar	Stem	Crank
SystemSix	KNØT64	Vittoria Rubino Pro Speed 23C	KNØT SystemBar	KNØT	HollowGram SiSl2
Trek Madone 9.9	Bontrager Aeolus 5	Bontrager R3 25C	Trek Madone	Integrated	Shimano 9100
Felt AR	Zipp 454	Continental GP4000S II 23C	Vision 4D MAS Flat	Vision Trimax	Shimano 9100
Cervelo S5 Team	Enve 4.5	Continental Grand Prix 23C	ENVE SES Carbon Aero	ENVE Carbon	Rotor 3D+
Specialized Venge Vias Disc Di2	Roval CLX 64	S-Works Turbo Cotton 26C	S-Works Aerofly Vias	S-Works Vias	S-Works Carbon
Giant Propel	Giant SLR	Giant Gavia 25C	Giant Contact SLR Aero	Contact SLR Aero	Shimano 9100
Canyon Aeroad	Zipp 454	Continental Force/Attack 25/23	Canyon H11 Aerocockpit CFD	Integrated	Shimano 9100
Pinarello Dogma F10	Shimano C60	Continental GP4000S II 25C	Vision 4D MAS Flat	Vision Trimax	Shimano 9100
Scott Foil	Zipp 454	Continental GP4000S II 25C	Syncros FOIL	Integrated	Shimano 9100

All bikes tested with the same saddle, saddle height, handlebar stack, cassette and chainring size.

Bicycles were tested as sold by the manufacturer in Dura-Ace Di2 specification.


vittoria CORSA GRAPHENE 2.0
KNØT SL
64
HOLLOWGRAM
vittoria CORSA GRAPHENE 2.0
KNØT SL
64
HOLLOWGRAM