AEOLUS XXX WHITEPAPER

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BONTRAGER

CONTENTS

EXECUTIVE SUMMARY

At Bontrager Wheelworks our goal is to research, analyze, design, and manufacture the best performing wheels available. Leveraging Trek's analysis capabilities, we optimized each rim shape for its specific use. After evaluating over 10,000 rim design iterations, we have created the best rim shapes and wheelsets available.

Aeolus D3 wheels launched in 2011 and have exceeded expectations from our pro racing team and customers around the world. We redesigned the lineup to create better wheels in every way. Like the last generation of Aeolus wheels, they have lower drag than the competition.

This time we also optimized the weight, stiffness, braking performance, and aerodynamic stability. Figure 1 below summarizes how Aeolus XXX provides best in class drag, side-force, and rim weight across each rim depth. This lets you ride faster, with more confidence across all conditions.

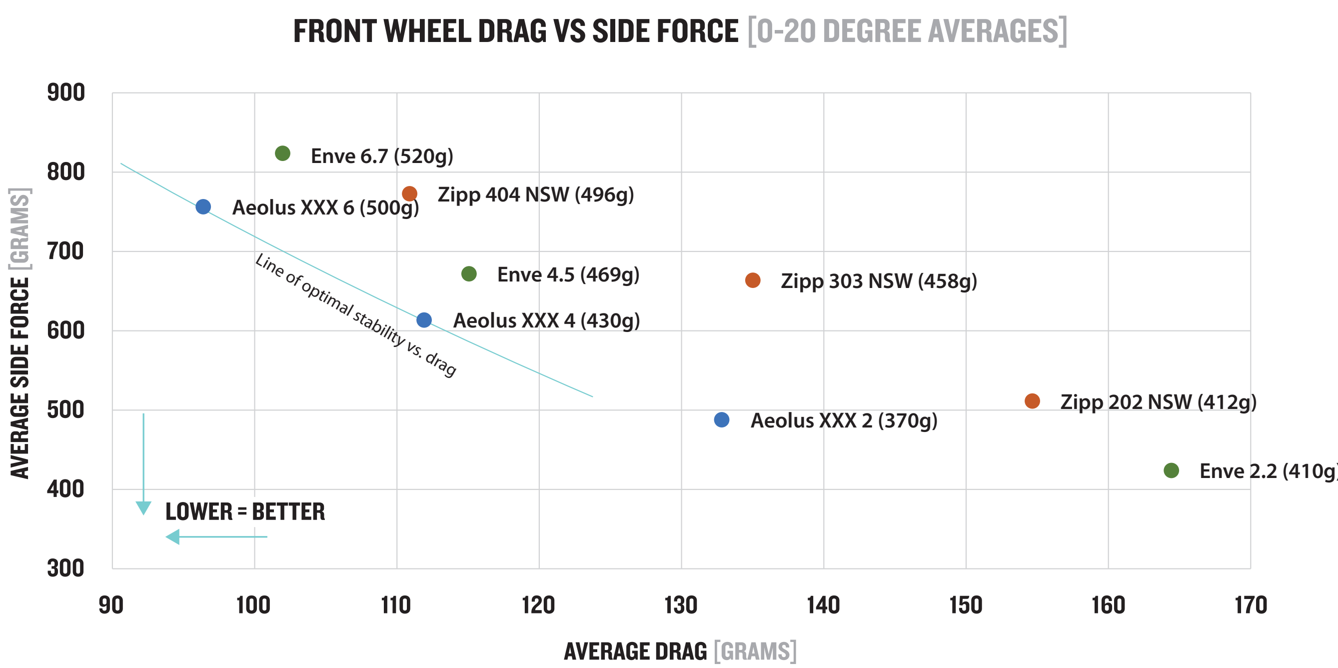


FIGURE 1
Front wheel drag vs side force (both averaged over 0-20 degrees yaw) and rim weight data for the Aeolus XXX lineup and BIC competitors

INTRODUCTION

Trek headquarters in Waterloo, WI houses the development and production teams that work on Aeolus XXX; from designers through rim molders and wheel builders. We re-thought and improved every process for Aeolus XXX. This results in the best performing wheels you can buy, period. Developed and tested with Trek Segafredo, they are unmatched in performance and excel in extreme environments.

The Aeolus XXX development goals were to improve on Aeolus D3 by refining its strengths while adding completely new technologies. We invested in new machinery that allows for drastically improved carbon braking performance wet and dry.

Using advanced FEA and CFD techniques along with optimization software, Aeolus XXX wheels set a new benchmark for wheel aerodynamics, stiffness, and weight. We created optimally shaped rims and paired them with the best components available. The final result is a family of wheels that lead the industry in stability, speed, and weight while maintaining that incredible Aeolus ride feel. This whitepaper will dive into all the details.

FIGURE 2

Aeolus XXX 6 wheels at the at the Wichita State University Walter H. Beech Wind Tunnel

DEFINING WHEEL PERFORMANCE

AERODYNAMIC STABILITY

Reducing aerodynamic drag can give a rider free speed but wheel stability is just as important of a consideration in overall rim design. By increasing wheel stability we can give a rider more confidence to ride a deeper wheel faster, and in more conditions.

The Aeolus XXX designs focus on making the fastest most ridable wheels possible. To do this, we performed a detailed research study on wheel aerodynamic stability. We started by comparing actual ride wind speed and yaw data with rider feedback indicating feelings of instability. This allowed us to identify riding conditions that make a wheel feel unstable. Results from this study showed that large changes in steering torque caused by high front wheel side force is the largest contributor to instabilities. We took this data and coupled it with actual wind tunnel runs of the same wheels at the same wind speed and yaw to identify specific crosswind forces that we needed to design for to make a to make consistently stable wheels. Read the Stability Testing section in supplemental information for more details on this study.

FIGURE 3
Aero Sticks capture yaw and wind speed data to better understand conditions that trigger rider feelings of instability.

AERODYNAMIC DRAG

One of the biggest advantages of deep section carbon wheels is a reduction in aerodynamic drag. This basically equates to a faster ride with the same input – free speed. Aeolus XXX wheels excel at this. At high speeds, these savings are substantial. Throughout this Whitepaper we compare products using wind tunnel measurements in grams of drag. Figure 4 below can be used to convert grams of wind tunnel drag to watts at various speeds. Almost all drag plots will be of front wheel only data. The front wheel makes up the majority of wheel drag, especially at low yaw. See the supplemental information 'In Bike Tunnel Testing' section for more details.

10 GRAMS WIND TUNNEL DRAG CONVERSION TO WATTS AT VARIOUS RIDING SPEEDS

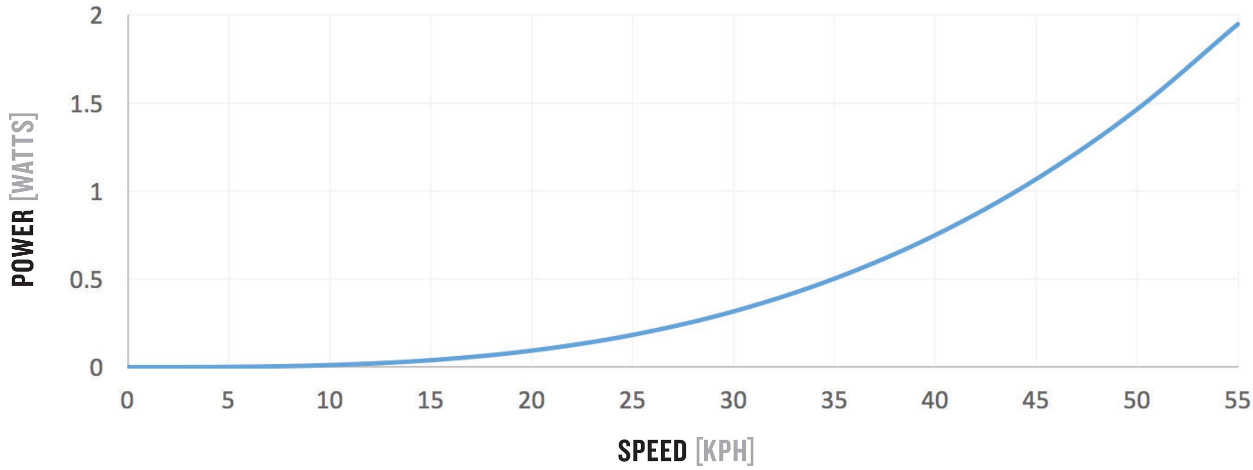


FIGURE 4

Speed vs. Power plot that can be used to convert 10 grams of wind tunnel aerodynamic drag to power in watts at various speeds

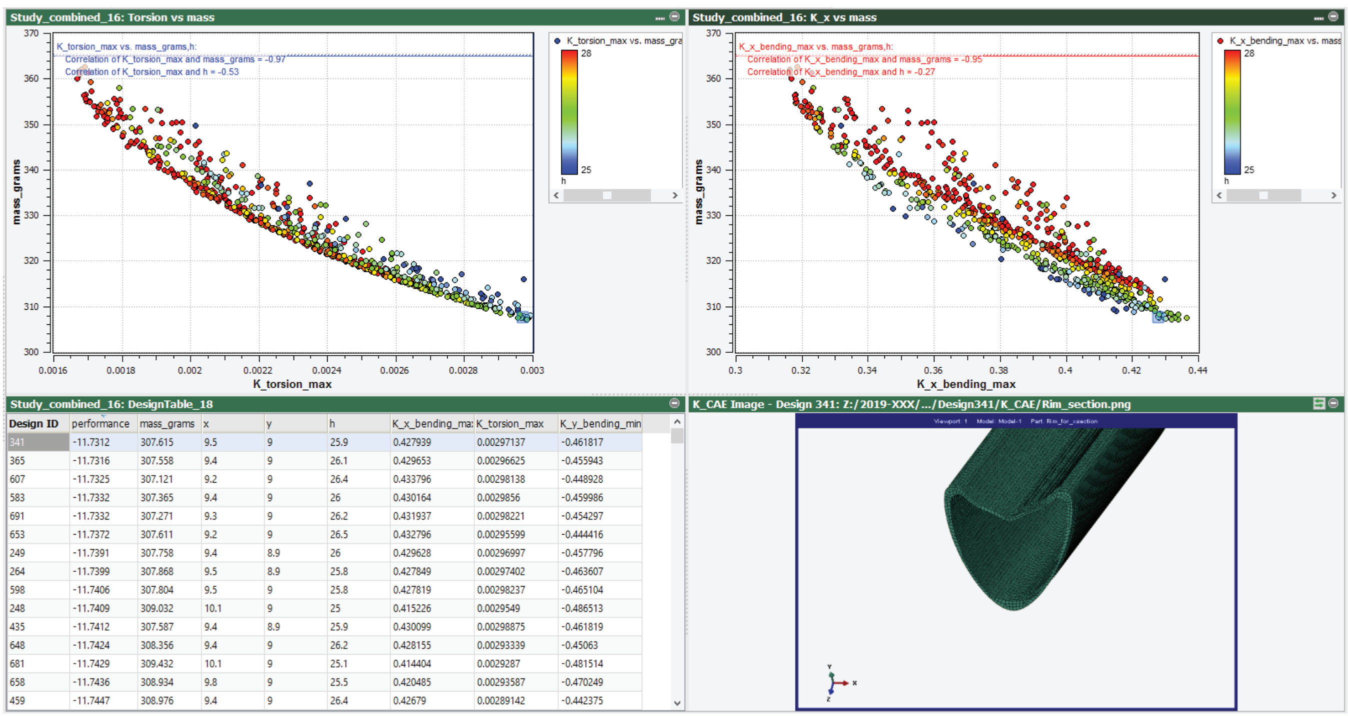
STIFFNESS AND WEIGHT

Low weight and sufficient stiffness are critical for acceleration and for a responsive wheelset. The wheel is a rotating mass, therefore grams in the rim contribute to the wheel's mass moment of inertia more than grams in the hub. As a result, low rim weight is crucial for quick acceleration. Aeolus XXX are some of the lightest rims on the market. See Table 1 to the right for Aeolus XXX weights vs. top competitors. We used FEA and laminate optimization to create an extremely light rim, that is strong and stiff without having a harsh ride. Read the 'FEA' and 'Optimization' portion of the development process section for more details.

Aeolus XXX clincher weights			
	Aeolus XXX 2	**Aeolus XXX 4**	**Aeolus XXX 6**
Rim weight	370g	430g	500g
Wheelset weight	1305g	1400g	1530g

Top competitor clincher weights			
	Zipp 202 NS	**Zipp 303 NS**	**Zipp 404 NS**
Rim weight	412g	458g	496g
Wheelset weight	1375g	1425g	1555g

TABLE 1
List of Aeolus XXX clincher rim and wheelset weights vs. the best-in-class competitors in each category



Design ID	performance	mass_grams	x	y	h	K_x_bending_ma:	K_torsion_max	K_y_bending_min
341	-11.7312	307.615	9.5	9	25.9	0.427939	0.00297137	-0.461817
365	-11.7316	307.558	9.4	9	26.1	0.429653	0.00296625	-0.455943
607	-11.7325	307.121	9.2	9	26.4	0.433796	0.00298138	-0.448928
583	-11.7332	307.365	9.4	9	26	0.430164	0.0029856	-0.459986
691	-11.7332	307.271	9.3	9	26.2	0.431937	0.00298221	-0.454297
653	-11.7372	307.611	9.2	9	26.5	0.432796	0.00295599	-0.444416
249	-11.7391	307.758	9.4	8.9	26	0.429628	0.00296997	-0.457796
264	-11.7399	307.868	9.5	8.9	25.8	0.427849	0.00297402	-0.463607
598	-11.7406	307.804	9.5	9	25.8	0.427819	0.00298237	-0.465104
248	-11.7409	309.032	10.1	9	25	0.415226	0.0029549	-0.486513
435	-11.7412	307.587	9.4	8.9	25.9	0.430099	0.00298875	-0.461819
648	-11.7424	308.356	9.4	9	26.2	0.428155	0.00293339	-0.45063
681	-11.7429	309.432	10.1	9	25.1	0.414404	0.0029287	-0.481514
658	-11.7436	308.934	9.8	9	25.5	0.420485	0.00293587	-0.470249
459	-11.7447	308.976	9.4	9	26.4	0.42679	0.00289142	-0.442375

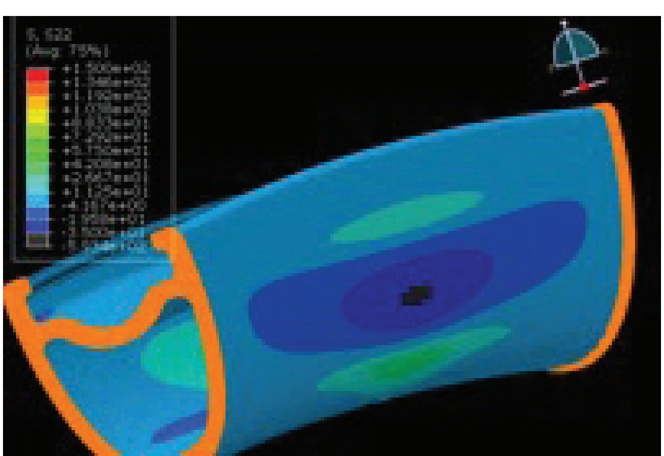
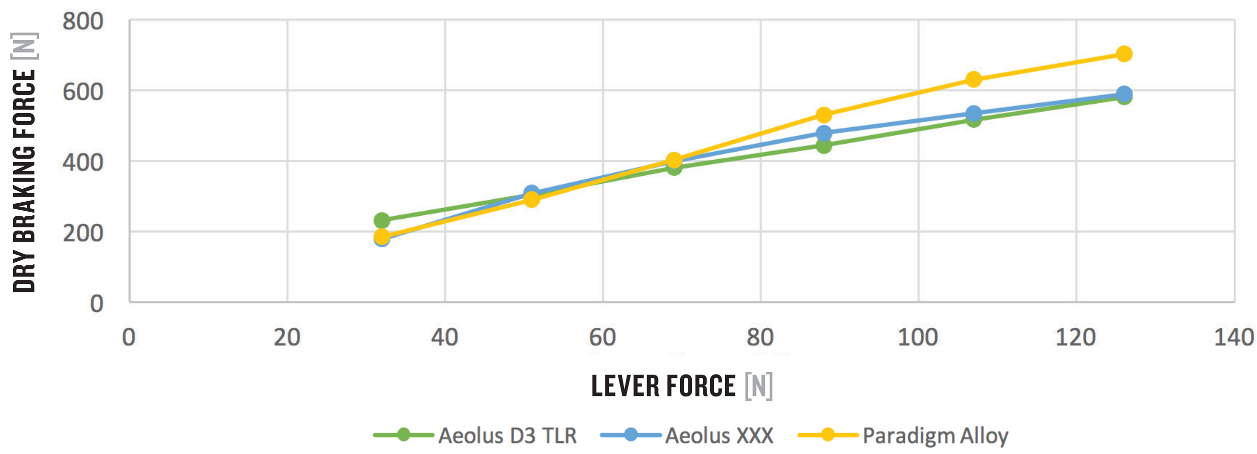


FIGURE 5
Photo above shows an example of outputs from the optimization software during Aeolus XXX 2 development. The left photo shows stresses from an Aeolus XXX 2 spoke bed push FEA simulation

BRAKING PERFORMANCE

Traditionally, braking on full carbon clinchers has never lived up to the performance of alloy rims in wet conditions. For Aeolus XXX, we developed a brake track to provide exceptional rim brake performance in wet and dry conditions. Trek invested in an automated laser machining center that roughens the brake track to an optimized level that maximizes braking performance when used with Black Prince pads. We call this technology Laser Control Track. Field and lab testing comparing Laser Control Track braking performance to the top competitors determined that the Laser Control Track is quieter, had better modulation, and gave a better sense of control than the competition. In addition, brake performance testing showed Aeolus XXX wheels to have braking performance directly comparable to alloy rims with significant improvements over prior carbon models. Laser Control Track rims are designed to work only with Swiss Stop Black Prince Pads. Figure 6 below shows some performance data.

LEVER FORCE VS. BRAKING FORCE - DRY CONDITION



LEVER FORCE VS. BRAKING FORCE - WET CONDITION

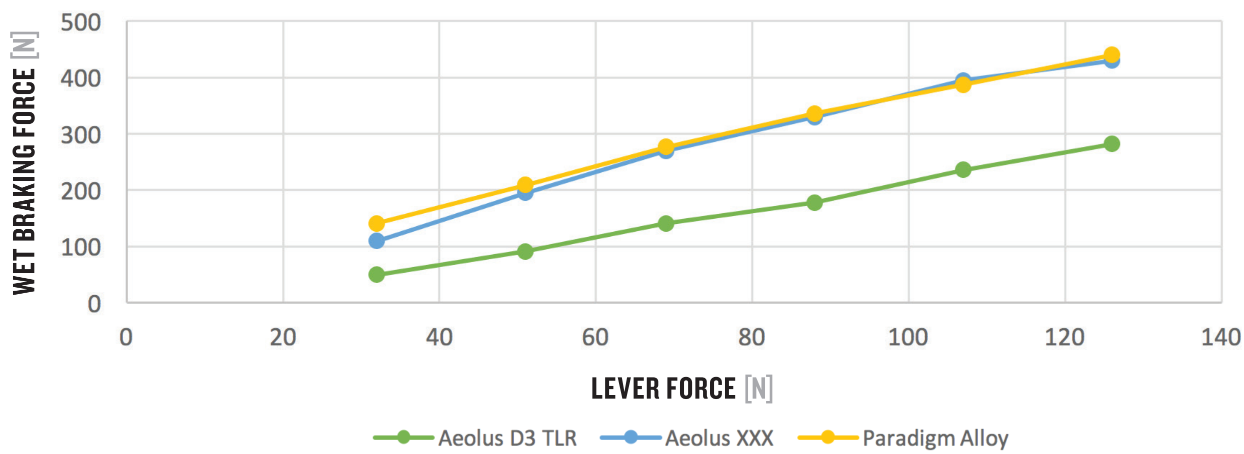


FIGURE 6

Braking lever force vs. braking force data for wet and dry conditions on Aeolus XXX with Laser Control Track, Aeolus D3 TLR, and Paradigm alloy rims

DEVELOPMENT PROCESS

Designing and Building the lightest, fastest, and most stable carbon road wheels available

It's easy to imagine the world's greatest innovations as spur-of-the-moment strokes of genius and inspiration, but the reality is that most of them are the result of countless hours of testing and research.

Aeolus XXX wheels are no different. We employed advanced modeling software to identify the rim shapes that would provide the light, aerodynamic, stable ride feel we desired, and then verified their success using the most stringent testing processes available.

Aeolus XXX are optimized for aerodynamics and have an inner width of 21mm for a great ride and tire support for traditional as well as larger road tires. Rim width development started by creating a CAD model to properly mimic all reasonable rim shapes and a clincher tire model that would properly change shape with varying rim width. We actually designed for the rim to shape the tire itself and then took the tire into consideration for our models to yield better overall system aerodynamic performance.

After finalizing shapes, we cut prototypes and validated the shapes in the wind tunnel. R&D rim tooling was cut for the final rim shape of each model and a laminate was developed using an iterative process. Composite laminates were taken from analysis and tested and adjusted until they exceeded structural goals. The final designs were stringently tested to Bontrager standards.

In the end, we optimized the shape of each wheel to fit its intended usage, ensuring that Aeolus XXX 2, 4, and 6 all provide the consistent industry leading performance that riders rely on.

We controlled this process every step of the way, from design, to prototyping, to machining the molds, all the way through carbon layup and wheel assembly. By controlling every process right here at our global headquarters in Waterloo, WI, we can consistently manufacture the very best carbon wheels available.

CAD CREATION

The first step in the development process is to create a CAD model that can be used for Computational Fluid Dynamics and structural analysis. The model must properly mimic the surfaces that that air will flow over for CFD analysis and rim wall thicknesses for structural FEA. They are setup as parametric models so specific variables can be adjusted to tweak the rim inner/outer width, rim depth, and rim sidewall shape. One key step for CFD is creating a tire model that correctly mimics an inflated tire and that changes shape like a real tire as the inner rim changes width. This allowed us to look for the ideal inner and outer rim width to use for aerodynamics with a 25c tire.

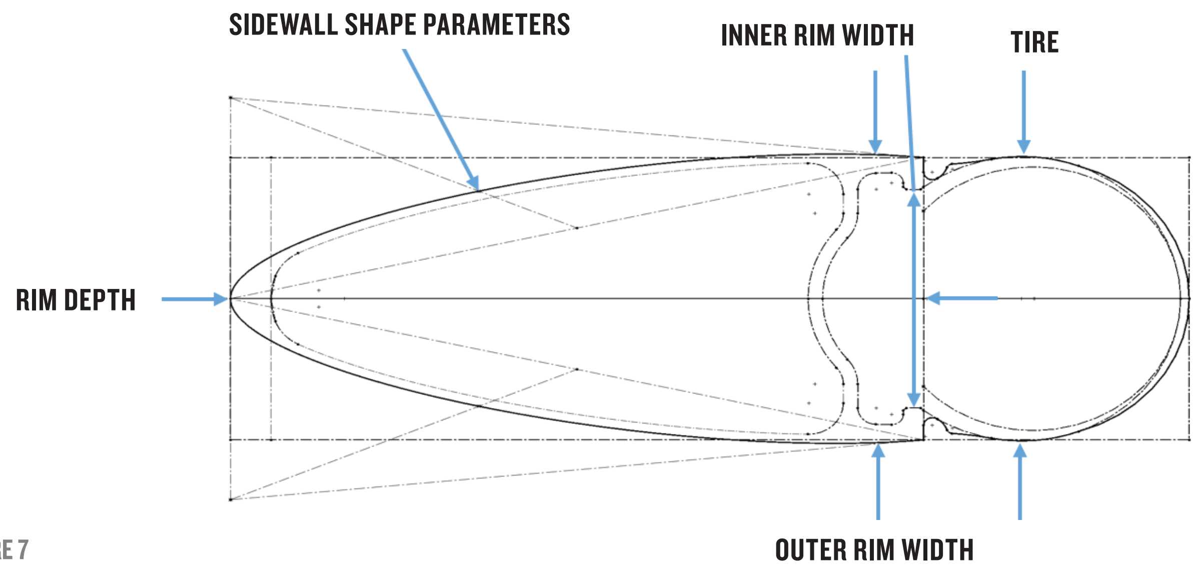


FIGURE 7
Sketch of CAD used during Aeolus XXX development with key variables

FINITE ELEMENT ANALYSIS (FEA)

The first step towards successful optimization is validated analytical models that predict the performance of the rim. Performance refers not only to the strength but also stiffness and compliance for ride quality. Trek has completed extensive testing to help develop and validate finite element models (FEMs) to simulate wheel impacts, predict stresses generated during spoke tensioning, and predict stiffness and compliance for ride quality load cases. FEA allows us to set structural parameters that will maintain both ride quality and the overall strength needed to pass our rigorous testing while still optimizing the rim to be as light as possible.

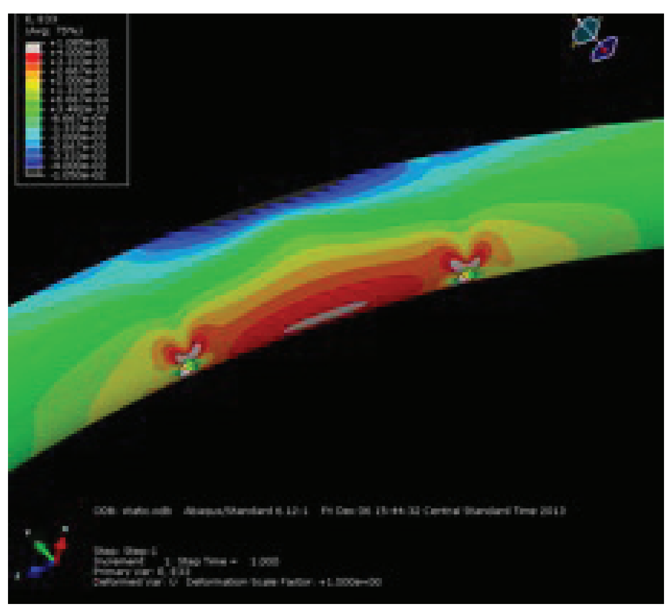
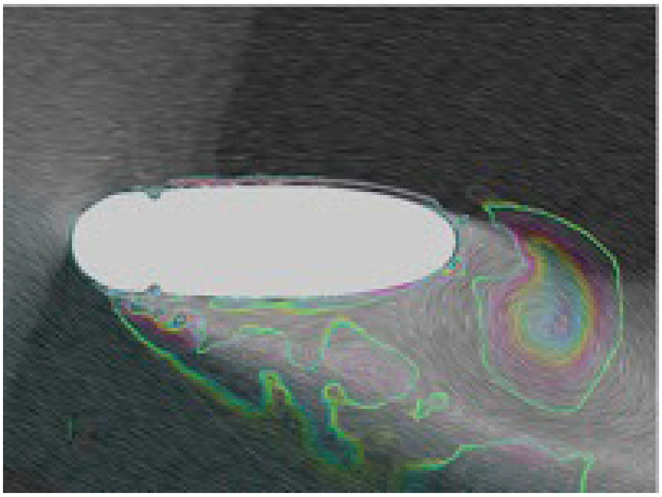


FIGURE 8
Finite element analysis from Aeolus XXX 2 development showing strains during an impact load case

COMPUTATIONAL FLUID DYNAMICS (CFD)

Drag and side force of rim shapes were evaluated using wind tunnel-tuned computational fluid dynamics (CFD). To optimize the computational time, a mix of two dimensional and three-dimensional methods were selectively used in analyzing particular aspects of air flow over the rim body. A creative use of 2D methods permits rapid computation while capturing the essential physics that attributes to skin friction and pressure drag. This was particularly suitable for the optimization process in which statistically meaningful sample numbers are needed to assess the correlation between drag and side force in relation to the rim geometry. Additionally a 3D method was employed to ensure the accurate understanding of stalling behavior. It also served as a secondary check for drag and side force prediction.



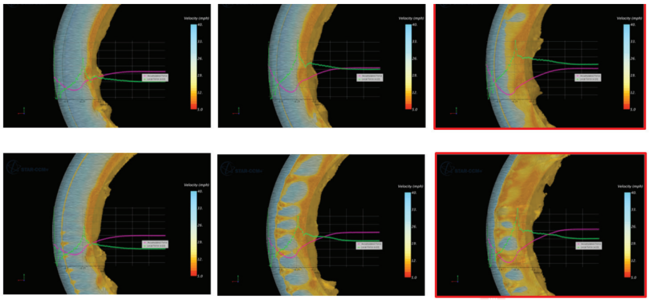


FIGURE 9

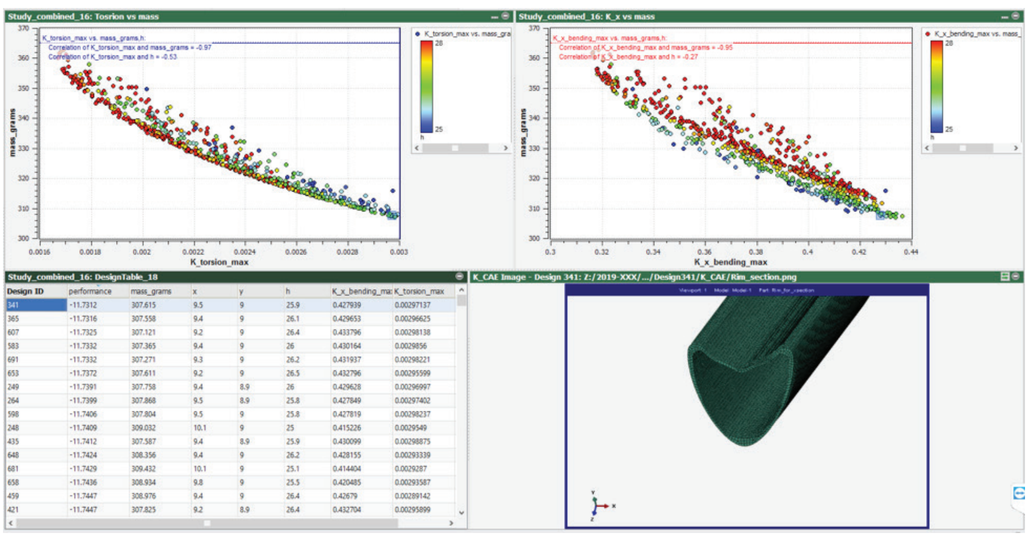
Images from two-dimensional and three-dimensional CFD. The visualization displays velocity vectors and wake turbulance.

OPTIMIZATION

Red Cedar Technology's HEEDS is a parameterized optimization software that integrates with CAE tools to drive an adaptive optimization search. HEEDS is driven by defining objectives (i.e. minimize weight, maximize stiffness), constraints (i.e. do not violate stress requirements), while altering parameters that drive the shape of the rim.

Optimization of the Aeolus XXX 2 rim profile focused on the structural objectives with weight being of utmost importance. HEEDS performs true multi-objective analysis. For such an analysis, there does not exist one best solution but many optimal solutions that are trade-offs between the objectives. One objective cannot be made better without compromising the other. These designs lie on what is called a Pareto front, a curve outlining the best possible combinations of the two competing parameters. Two such Pareto Fronts can be seen in figure 8 below.

Note that a design that lies on the Pareto front for weight versus torsional stiffness (top left) does not necessarily lie on the Pareto front for weight versus bending stiffness (top right). The use of software like HEEDS is extremely important to explore the design space intelligently and efficiently using a hybrid genetic optimization algorithm. Many hundreds of designs can be automatically evaluated and complete (or converged) Pareto fronts generated. This provides the engineer a vast amount of data to evaluate and use to arrive at the best rim for a given application. With this process we were able to test over 10,000 rim designs, always working toward the best.



Design ID	performance	mass_grams	x	y	h	K_x_bending_ma:	K_torsion_max
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248	-11.7409	309.032	10.1	9	25	0.415226	0.0029549
435	-11.7412	307.587	9.4	8.9	25.9	0.430099	0.00298875
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658	-11.7436	308.934	9.8	9	25.5	0.420485	0.00293587
459	-11.7447	308.976	9.4	9	26.4	0.42679	0.00289142
421	-11.7447	307.825	9.2	8.9	26.4	0.432704	0.00295899

FIGURE 10

An example of HEEDS optimization software output during Aeolus XXX 2 development

Aeolus XXX 2, with a 28mm depth saw lightweight prioritized ahead of drag to result in a lighter wheel that still performs exceptionally well in the wind tunnel while the 60mm Aeolus XXX 6 and 47mm Aeolus XXX 4 prioritized aerodynamic speed and stability foremost.

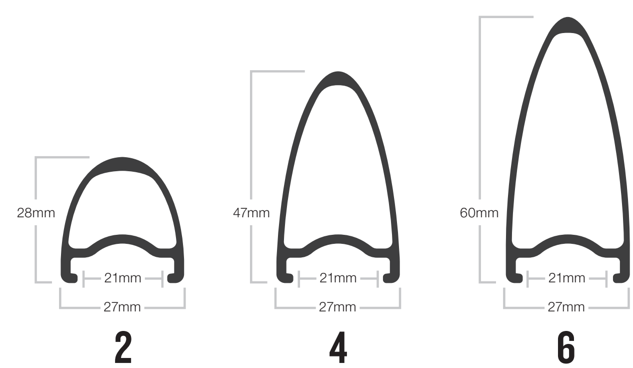


FIGURE 11

Rim sections of Aeolus XXX 2, XXX 4, and XXX 6 Clinchers.

OPTIMIZATION CONTINUED

For optimizing XXX4 and XXX6 rim profiles, HEEDS' performance objectives were set for minimizing drag whiles simultaneously minimizing side force. For each rim design, drag and side force were computed for five yaw angles ranging from 0 to 20 degrees. After noting pre-and post-stalling behavior, 0-20 degree yaw average of forces was taken to map out the ranking of each design in the drag-side force design space as seen in figure 12. In this design space, when the rim surface geometry information is added, the trends in drag and side force against the rim shape become clear.

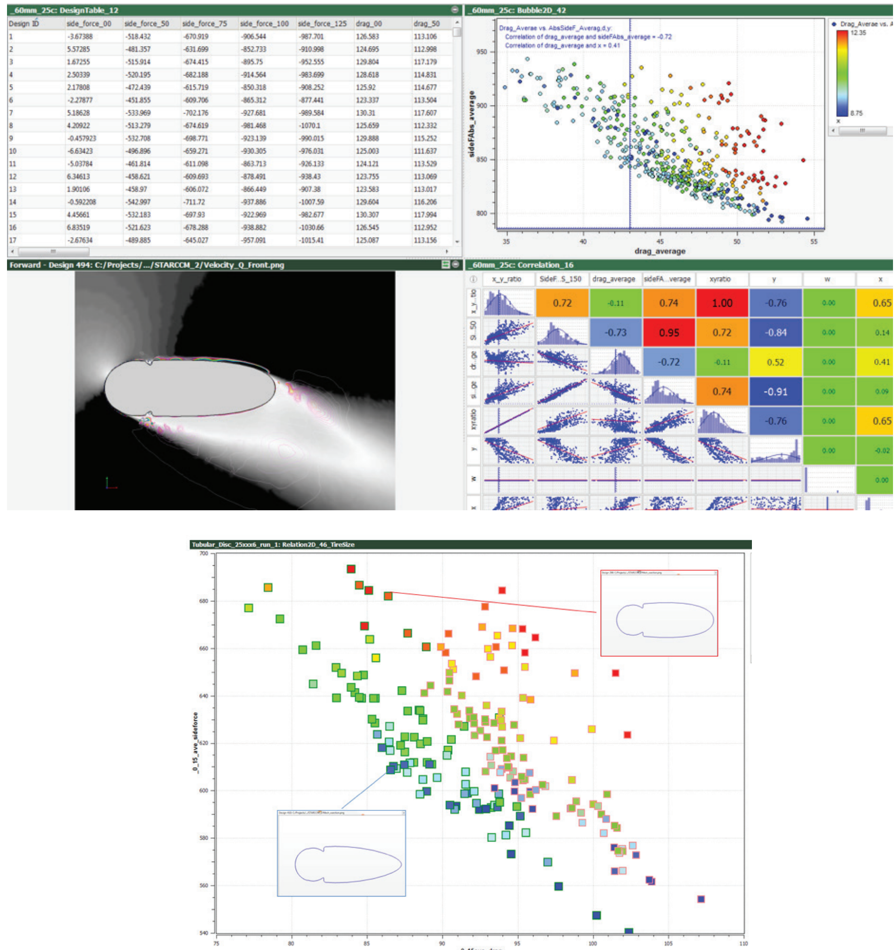
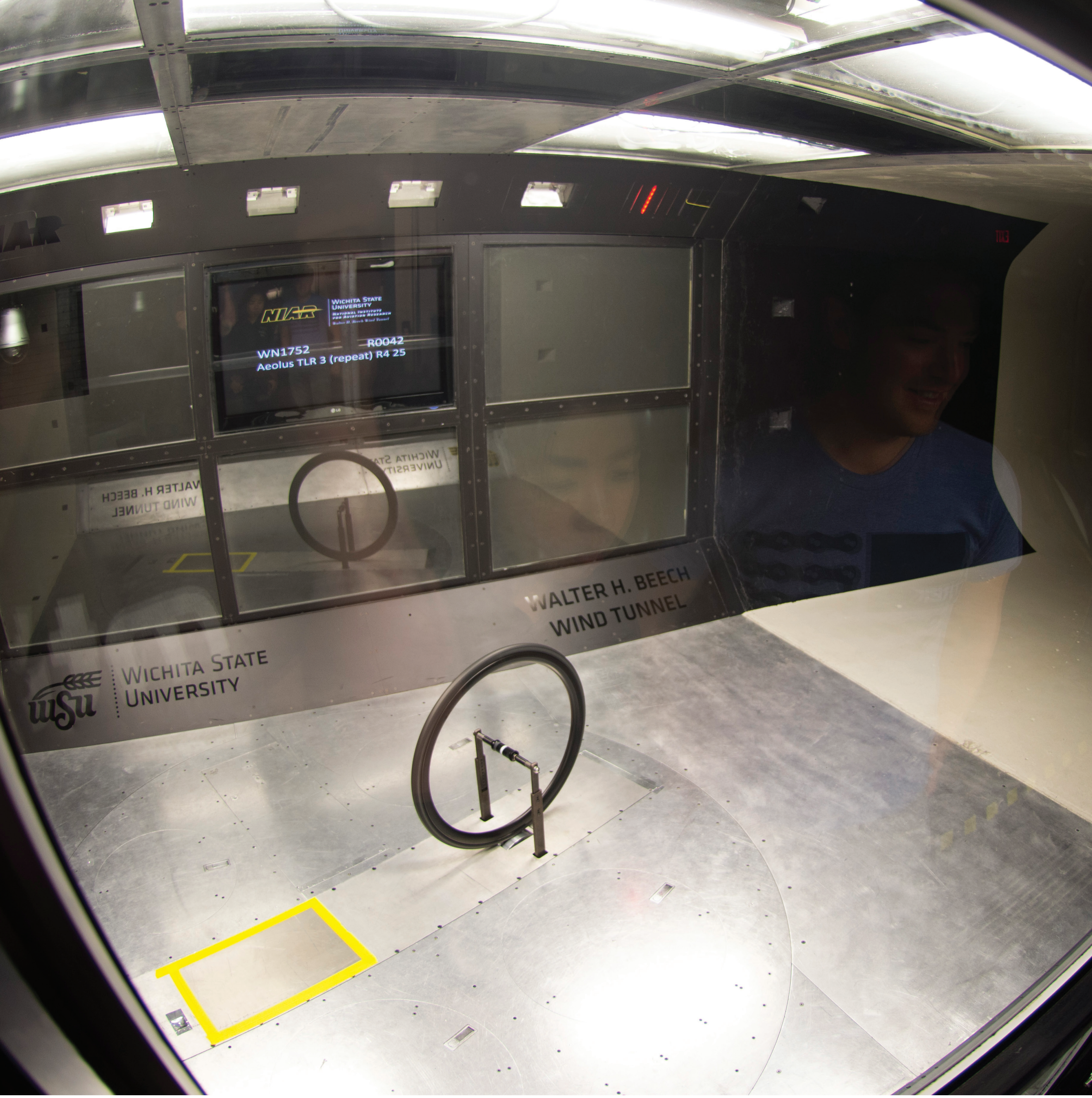


FIGURE 12

An example of HEEDS optimization software output during Aeolus XXX 6 development



PROTOTYPING AND WIND TUNNEL TESTING

After narrowing in on final shapes, the Trek prototype group machined three solid prototypes per model for wind tunnel validation. These shapes were chosen from a small zone on the optimal Pareto front for drag/stability and had relatively similar shapes. The wind tunnel testing served as a confirmation of CFD and helped select the best out of a small group of optimal shapes. Specifics about the wind tunnel testing are discussed in the Supplemental information 'Testing details' section.

R&D/VALIDATION TESTING AND MANUFACTURING

Once the final shapes have been determined, the next major step of the development process is designing the composite manufacturing process and laminate, determining the proper wheel build, testing this system, and implementing everything in production.

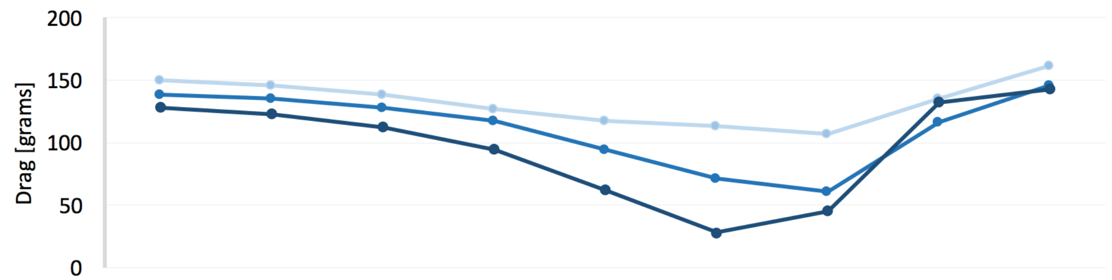
We test for all industry required standards along with more stringent Bontrager standards including: rolling fatigue, brake heat performance, braking coefficient of friction, impact, spoke bed strength, and ultimate pressure testing. During the implementation into production manufacturing, a large batch of rims are tested and must pass before production approval. For the product life in production a percentage of rims are randomly pulled and tested to confirm several critical tests.

Additional field testing with team riders from Trek-Segafredo further validate final designs and continue to test wheel durability in the real world under the most extreme users.

AEOLUS XXX PERFORMANCE

Structural and CFD optimizations helped us find significantly better shapes than anyone else in the marketplace. The resulting shapes and process are patent pending. In the following section, the Aeolus XXX lineup will be introduced and compared with our top competitors. All drag and side force measurements are of front wheel only with a Bontrager 25c R4 tire and were taken during the same test day at the Wichita State University (WSU) wind tunnel.

FRONT WHEEL DRAG



FRONT WHEEL SIDE FORCE

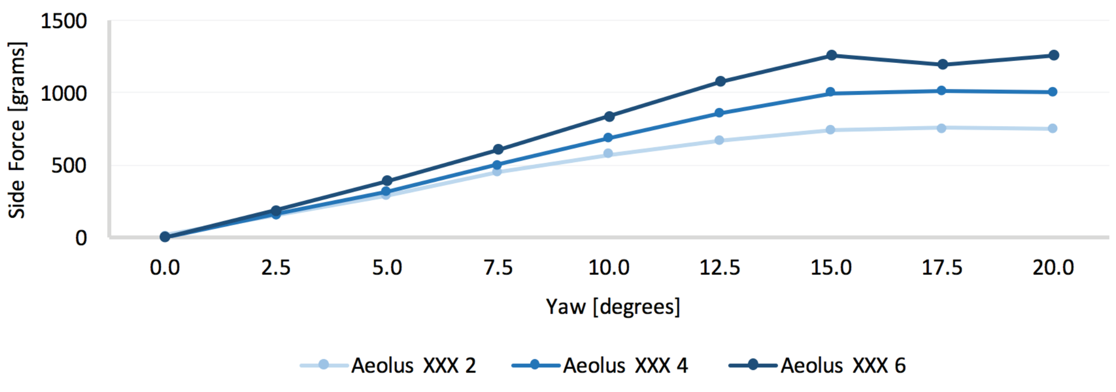


FIGURE 13
Front wheel drag and side force measurements for the Aeolus XXX clincher lineup with a R4 25c tire

AEOLUS XXX 2

The lightweight climber, strong enough for cyclocross and gravel riding.

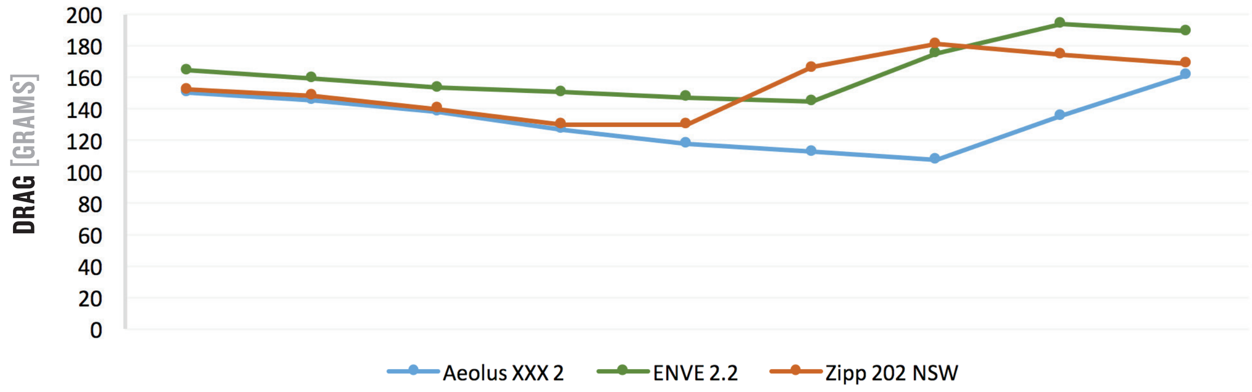
The Bontrager Aeolus XXX 2 is unbelievably light, yet stiff enough to be a confident handling wheelset with a great ride feel. It's perfect for a day in the mountains and strong enough to stand up to Cyclocross and gravel use. The rim section was optimized for weight and stiffness yet keeps some of the Aeolus XXX features that create low drag for its depth. The XXX 2's are faster (0-20 yaw average) than Zipp 303 NSW with 17mm less depth and 120 grams less weight per wheelset. Side forces are low enough for wheels in this category that cross wind handling isn't an issue. Overall, this wheelset is lighter and faster than the competition while maintaining a great ride feel.

	Aeolus XXX 2	Zipp 202 NSW	ENVE 2.2
Rim weight	370g	412g	410g
Rim Depth	28mm	32mm	25mm
Rim Inner Width	21mm	16.25mm	18.5mm
Brake Track Width	27mm	25.4mm	27mm
Wheelset Weight	1305g	1375g	1375g

TABLE 2
Aeolus XXX 2 and top competitors rim and wheelset specifications.

FRONT WHEEL DRAG

Aeolus XXX 2 vs. competition



FRONT WHEEL SIDE FORCE

Aeolus XXX 2 vs. competition

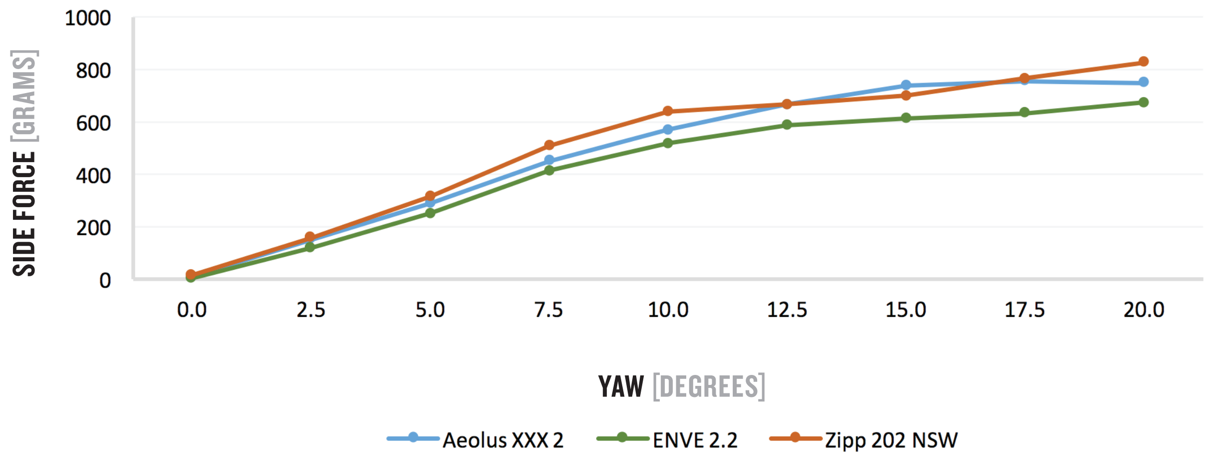


FIGURE 14

Front wheel drag and side force measurements for the Aeolus XXX 2 clincher and top competitors with an R4 25c tire

AEOLUS XXX 4

The do-it-all workhorse, fast and stable for everyday aero.

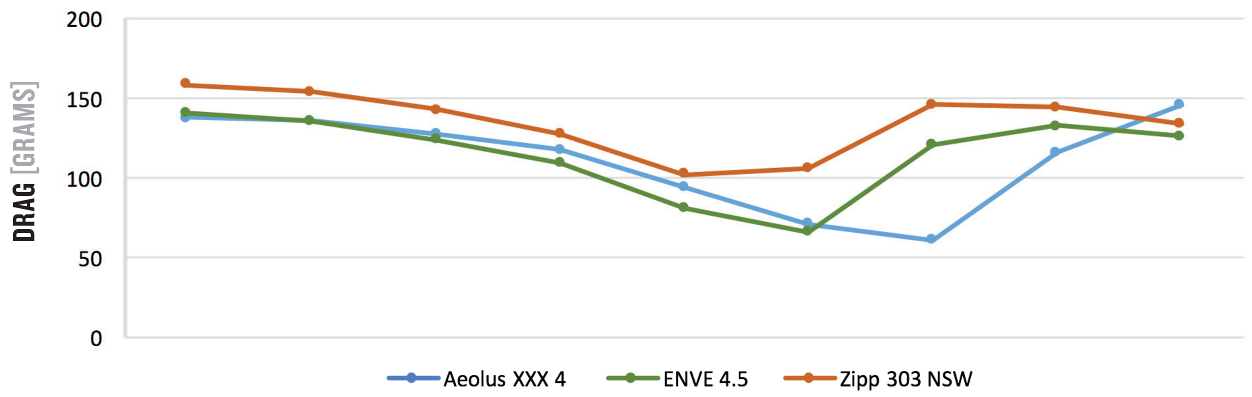
The Bontrager Aeolus XXX 4 is the all-rounder. Light enough for mountain stages and fast enough for a triathlon. They will improve the ride of any racing bike. The rim shape is optimal for low side force making it ridable in nearly all conditions. Aeolus XXX 4 provide best in class weight, speed, and stability. In fact, they are close to matching the speed of Zipp 404 NSW's while being 155 grams lighter per wheelset, 13mm shallower, and having 20 percent lower front wheel side force, see Aeolus XXX 6 performance breakout for 404 NSW performance data.

	Aeolus XXX 4	Zipp 303 NSW	ENVE 4.5 (front rim)
Rim weight	430g	458g	469g
Rim Depth	47mm	45mm	48mm
Rim Inner Width	21mm	16.25mm	18.5mm
Brake Track Width	27mm	26.4mm	27mm
Wheelset Weight	1400g	1425g	1526g

TABLE 3
Aeolus XXX 4 and top competitors rim and wheelset specifications.

FRONT WHEEL DRAG

Aeolus XXX 4 vs. competition



FRONT WHEEL SIDE FORCE

Aeolus XXX 4 vs. competition

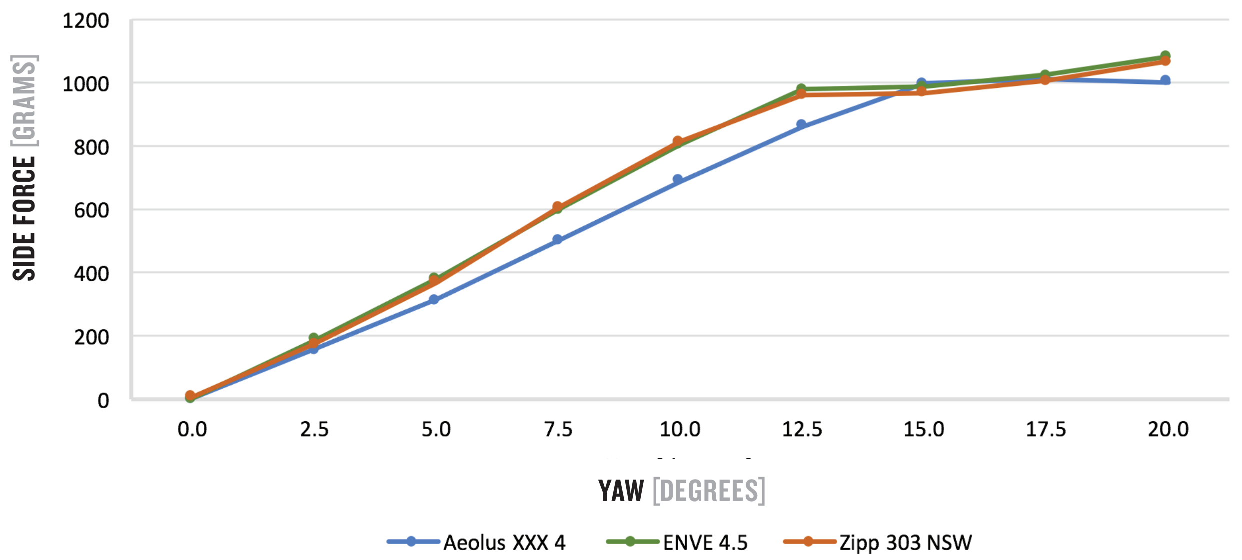


FIGURE 15

Front wheel drag and side force measurements for the Aeolus XXX 4 clincher and top competitors with an R4 25c tire

AEOLUS XXX 6

Speed with unmatched stability that brings an ultra-aero wheel to more riders and conditions.

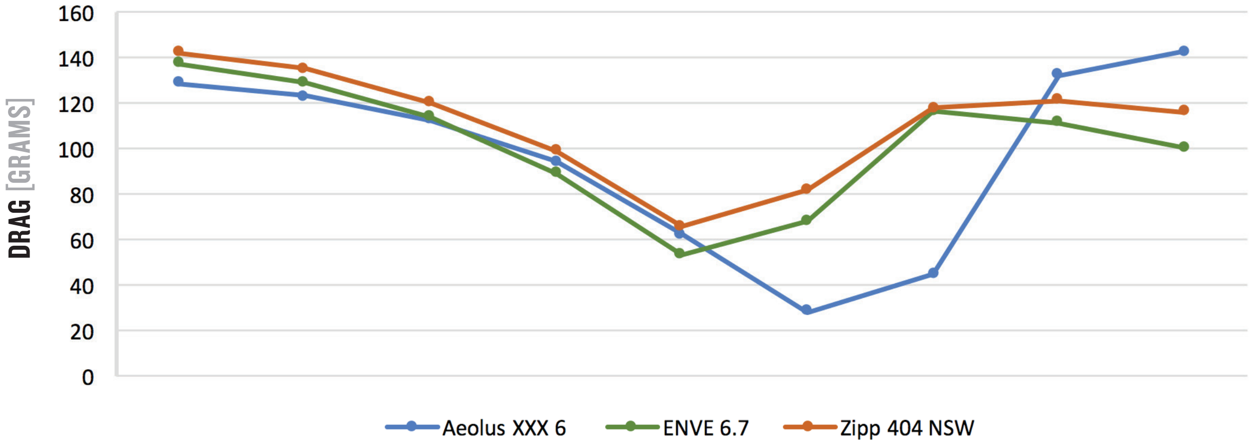
The Bontrager Aeolus XXX 6 is lightning fast yet has great aerodynamic stability. Aeolus XXX 6 has the speed of the previous generation 70mm deep Aeolus 7, but the handling and stability of the previous generation 50mm deep Aeolus 5. Lighter and wider then Zipp 404 NSW and ENVE 6.7, Aeolus XXX 6 is faster and has significantly lower side force at almost all yaw angles. Aeolus XXX 6 is the most ridable super aero wheelset available.

	Aeolus XXX 6	Zipp 404 NSW	ENVE 6.7 (front rim)
Rim weight	500g	496g	520g
Rim Depth	60mm	58mm	60mm
Rim Inner Width	21mm	17.25mm	18.5mm
Brake Track Width	28mm	26.4mm	26mm
Wheelset Weight	1530g	1555g	1554g

TABLE 4
Aeolus XXX 6 and top competitors rim and wheelset specifications.

FRONT WHEEL DRAG

Aeolus XXX 6 vs. competition



FRONT WHEEL SIDE FORCE

Aeolus XXX 6 vs. competition

FIGURE 16

Front wheel drag and side force measurements for the Aeolus XXX 6 clincher and top competitors with an R4 25c tire

AEOLUS XXX DEFINING TECHNOLOGIES

LIGHTER, FASTER, MORE STABLE

The all-new Aeolus XXX wheels are built on a wider rim with a redesigned shape that's faster, lighter, and more stable in all conditions—including crosswinds. Now you can run a deeper, more aerodynamic wheel with more confidence than ever.

LASER CONTROL TRACK

Confidence to ride your fastest requires absolute confidence in your ability to stop. The all-new Laser Control Track massively improves braking performance for stopping power directly comparable to alloy rims, even in wet conditions.

SPEED STABILITY SHAPING

On the open road, wind comes from all different directions. That's why we redefined a high-performance wheel to be one that does more than cut through headwinds in a wind-tunnel. Aeolus XXX is optimized for stability in real-world conditions, for the best performance in even the strongest crosswinds.

ALL NEW WIDER SHAPE

Aeolus XXX benefits from a wider 21mm internal rim and all-new shapes optimized for each depth and intended use. The result is best-in-class aerodynamics and stability at all three rim depths.

OCLV XXX CARBON

OCLV XXX Carbon is made from advanced aerospace materials right here at Trek's Global Headquarters in Waterloo, Wisconsin, USA.

CARBON CARE LOYALTY PROGRAM

Bontrager's Carbon Care wheel program offers solutions for wheel damage that occurs outside warranty so that you can ride to your limit without worry.

SUPPLEMENTAL INFORMATION

UNDERSTANDING STABILITY

What do we mean when we talk about instability and side force? Grab a bike and do the following experiment. Hold the bike by the top tube and push with a side force into the front wheel at the skewer. What happens? The most apparent action is the front handlebar steers in the direction you are pushing. The same thing happens when riding in a crosswind. Crosswinds can create forces similar to this and can be uncomfortable to ride in. Most aerodynamic wheel instabilities come from front wheel forces acting on the steering. That's why riders can comfortably use deeper rear wheels then front wheels on windy days. To design a wheel that performs better in these challenging conditions, we need to fully understand all the forces acting on the wheel.

During wind tunnel testing we measure all the aerodynamic forces acting on a front wheel. The terms for these forces are side force, drag, and lift and the moments are pitching moment, rolling moment, and yawing moment. Drag is most commonly discussed in the cycling industry because it directly relates to your speed. Several of these aerodynamic forces contribute to a steering torque. The yawing moment, rolling moment, and side force all have components that will contribute to steering torques.

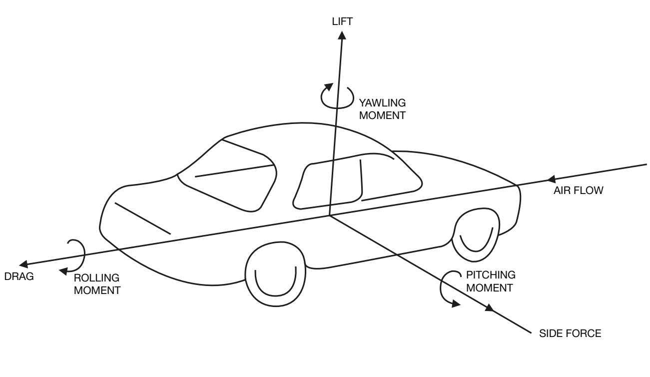


FIGURE 17

Diagram of forces measured during wind tunnel testing

Moments can be harder to visualize then forces. Imagine a rudder on a boat. As the rudder turns the boat wants to rotate due to the asymmetry. For a front wheel as the wind flows over the wheel from an angle (yaw) the asymmetry of the shape creates moments. Due to the steering geometry of a road bike some of the forces and moments acting on the front wheel will react out as a steering torque. The front tire contacting the ground reacts against the side force and creates a moment about the steering axis. This is what happened in the experiment pushing on the front wheel skewer. The yawing and rolling moments are partially in the direction of the steering axis and a component of them will act towards the steering torque. See the Free Body Diagram in figure 18 below to visualize how this works.

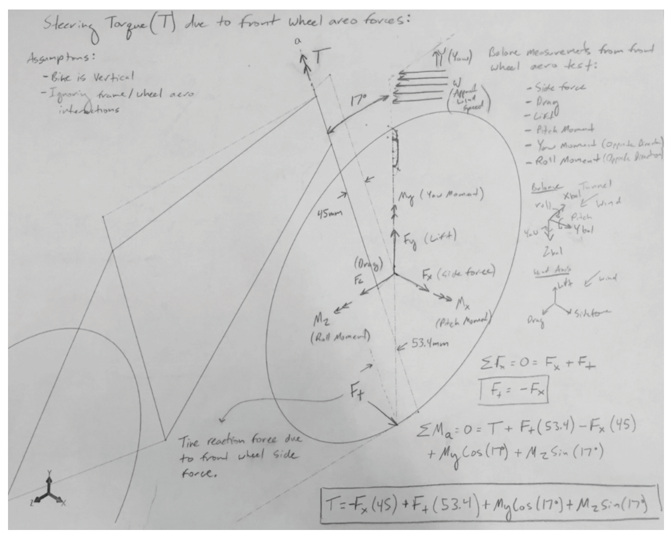


FIGURE 18

Free Body Diagram (FBD) showing how front wheel aerodynamic forces influence steering torque.

The steering geometry of a road bike and the magnitude and direction of the yawing and rolling moments make front wheel side force the main component acting as the aerodynamic steering torque. The aerodynamic moments play a role but are much smaller and often in the opposite direction then the side force component. For this reason, we focused on minimizing side force and for simplicity only show side force results throughout the whitepaper. Figure 19 to the right shows a breakout of how these components contribute to the total aerodynamic steering torque for Aeolus XXX 4.

Our theory was that a moderate constant steering torque is manageable but large changes in steering torque cause most feelings of instability. To prove this, we set out to take field measurements using a real-world testing scenario and see if we could create stability criteria.

BREAKOUT OF STEERING TORQUE COMPONENTS

Aeolus XXX 4 wheel calculations

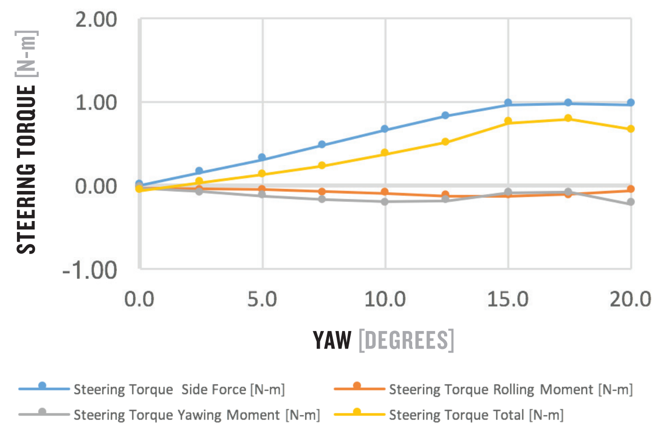


FIGURE 19

Breakout of components measured in the wind tunnel that make up the total steering torque.

STABILITY TESTING

Steering torque change >.75 [N-m] in < 1.4 sec

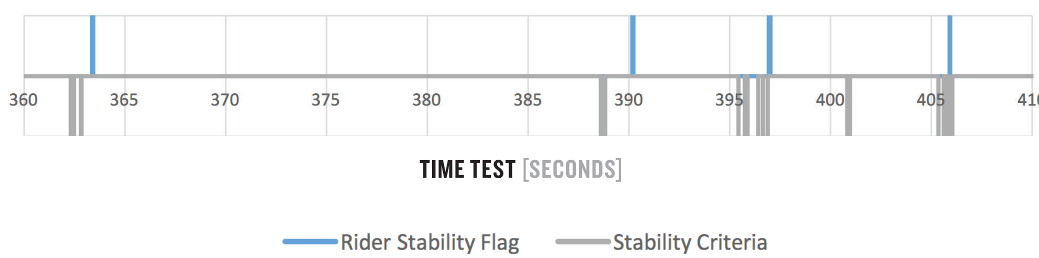


FIGURE 20

Plot of a real-world test duration showing where the rider noted instabilities and flags of the stability criteria.

We set up a Madone with an Aero Stick yaw and wind speed sensor and tested different wheels on a windy day. When the test rider felt unstable they flagged the data so we could determine what caused the instability. We took this ride data and calculated what steering forces we expected the tester to be experiencing by extrapolating from what we measured for the same wheel system in the wind tunnel. Reviewing this data, we could realize what conditions and forces made them feel unstable. We found that changes in steering torque greater than .75 Newton-meters in less than 1.4 seconds flagged an instability. We set this as our stability criteria and measured and calculated this data for multiple wheelsets. Using this criteria, we could estimate when instabilities would occur for this rider. These estimates matched up well with what the tester flagged as instabilities. Figure 20 is an example of 70 seconds of real world testing where we calculated for this stability criteria and marked the test rider's flagged instabilities. You can see that the rider flagged the same instabilities that our model predicted.

Finding these instabilities is interesting because we can look at what was happening with the wind during these occasions. We found that instabilities do not always happen during a stall or at high yaw angles. The instabilities happened at high yaw, both past and during stall, and at relatively low yaw well below stall. The only requirement is the change causes a large enough steering torque change in a brief time. Figure 21 shows data for the last 3 of these 4 instabilities shown in figure 20. To summarize, large changes in steering torque in a short amount of time caused by fluctuations in wind speed or direction on deep aero wheels are the primary cause for instabilities. Front wheel side force along with a road bike's geometry is the largest contributor to steering torque. During Aeolus XXX development we optimized the shapes so front wheel side force is minimized along with drag. This results in Aeolus XXX being the most ridable wheels for their speed.

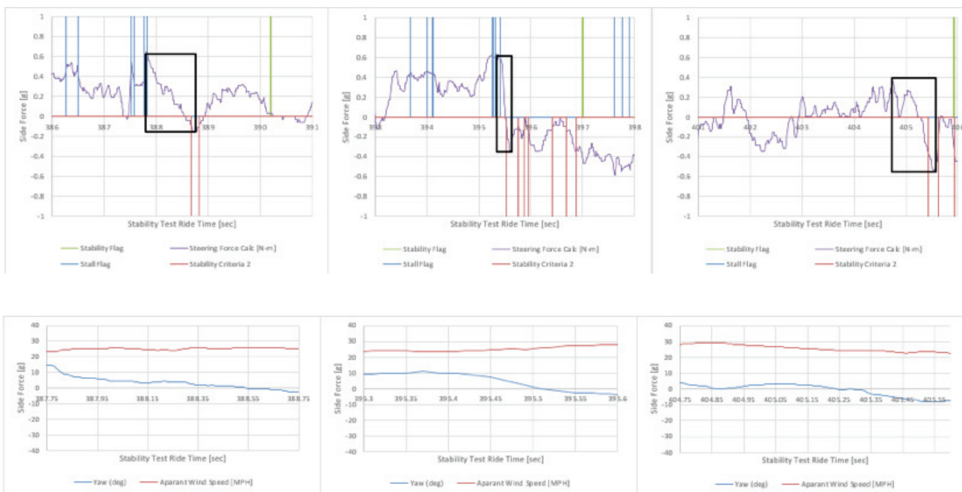
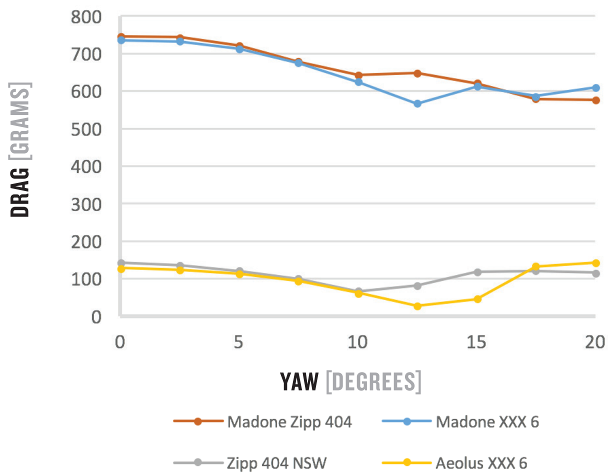


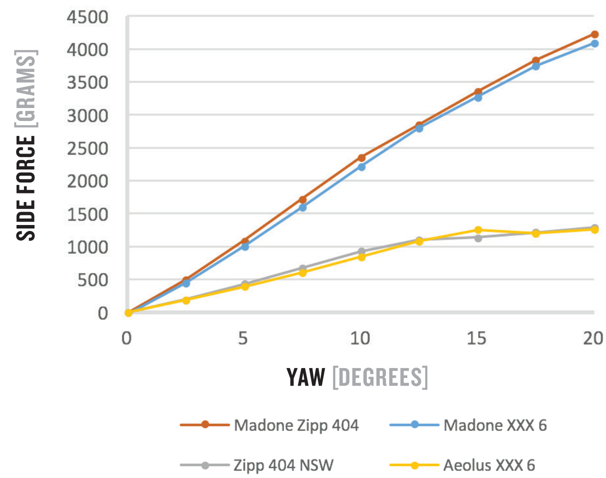
FIGURE 21

Wind conditions and calculated steering torque for the last 3 instabilities shown in figure 20

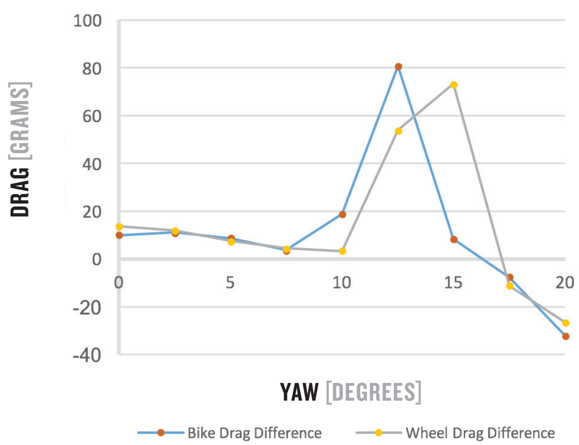
BIKE VS FRONT WHEEL ONLY DRAG
Aeolus XXX 6 vs Zipp 404 NSW



BIKE VS FRONT WHEEL ONLY SIDE FORCE
Aeolus XXX 6 vs Zipp 404 NSW



BIKE AND FRONT WHEEL ONLY DRAG DIFFERENCE
Zipp 404 NSW Minus Aeolus XXX 6 Drag



BIKE AND FRONT WHEEL ONLY SIDE FORCE DIFFERENCE
Zipp 404 NSW Minus Aeolus XXX 6 Side Force

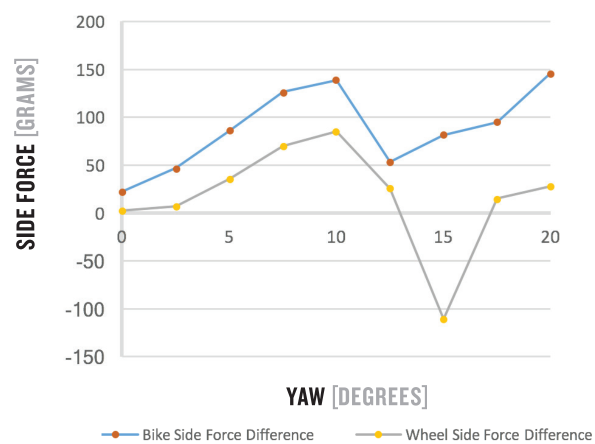


FIGURE 22
Comparison data of front wheel only and bike and wheelset data for Aeolus XXX 6 and Zipp 404 NSW

WHEEL-IN-BIKE TUNNEL TESTING

All previous wind tunnel results listed in this whitepaper are for front wheel only. As discussed in the 'Stability testing' section this data is critical for understanding a wheel's stability. Front wheel drag is also a good representation of how the overall wheel system will perform for drag. This section gives a comparison of wheel only to wheel in bike drag and side force for Aeolus XXX 6 and Zipp 404.

In the 'Difference' plots in figure 22 above positive values indicate that Aeolus XXX 6 performs better. Figure 22 shows that there is a good correlation between front wheel only and wheel and bike drag differences especially a low yaw. At higher yaw, the values are similar but the bike and wheel system stall slightly earlier. Side force differences have a larger offset but largely follow the same pattern. Again, the stall characteristics were affected by the bike stall. Wheel stall played a smaller role for the full bike and wheel system side force. During Madone development testing was also done to validate full bike tunnel testing vs. real world bike and rider drag.

TESTING DETAILS

WIND TUNNEL TESTING

Since late 2013, Trek has been using Walter H Beech Tunnel at National Institute of Aviation Research (NIAR, http://www.niar.wichita.edu/) located on the campus of Wichita State University. To make the tunnel bicycle-testing compatible, Trek has successfully built and installed a proprietary bicycle mount with an internal motor that drives the motions of bike wheels.

Trek follows a strict tunnel testing protocol. To document tunnel's operating condition on the test day, WSU created an aluminum disk that is tested at the beginning of each test day as a calibration device. The results from the calibration disc also tell us variation in measurements for tests that are months apart.

For wheel-only testing, the test wheel (front) is mounted on the bike mount's rear struts. For a typical wheel test, the inlet air speed is set to 30mph, and dynamics pressure (q =1/2 rho v^2) is held constant throughout the test.

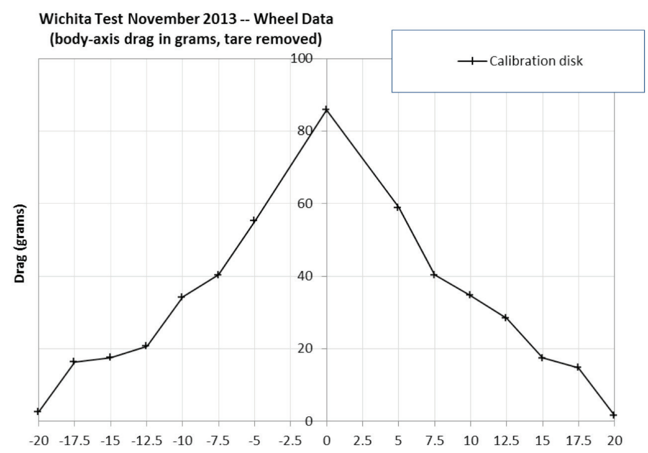
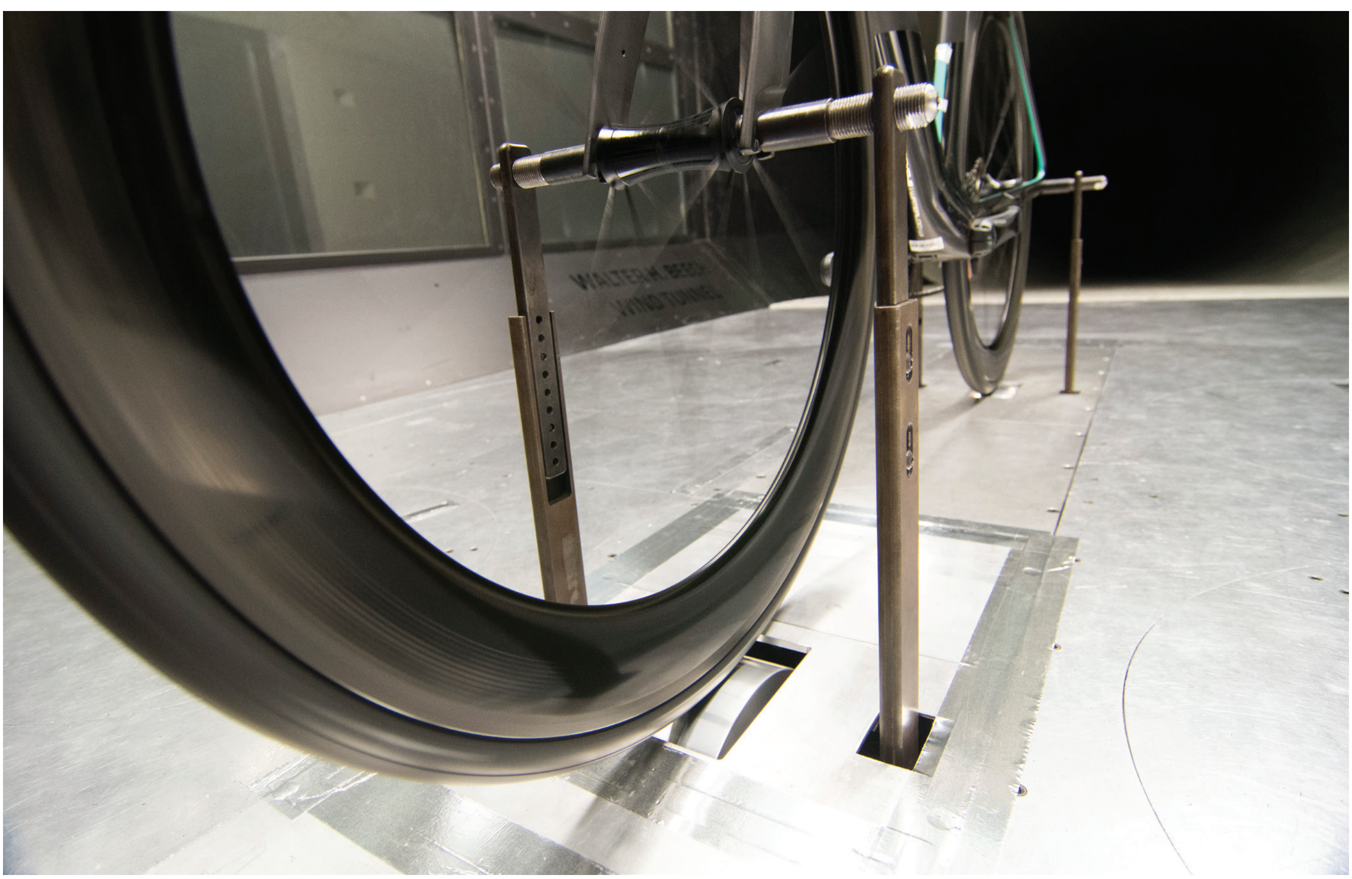


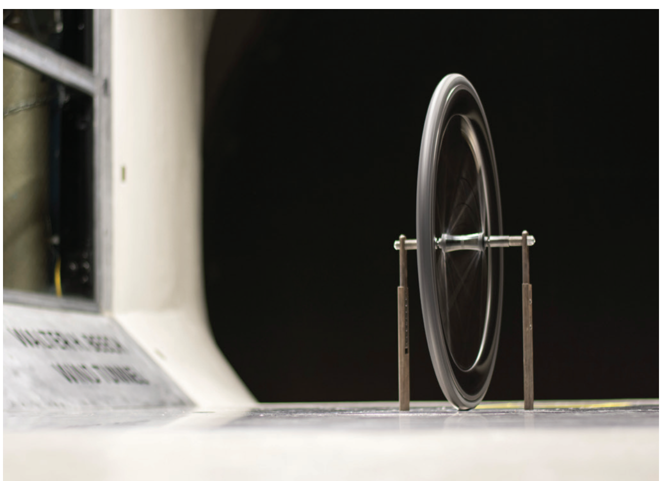
FIGURE 23
Drag vs. yaw result of the aluminum calibration wheel

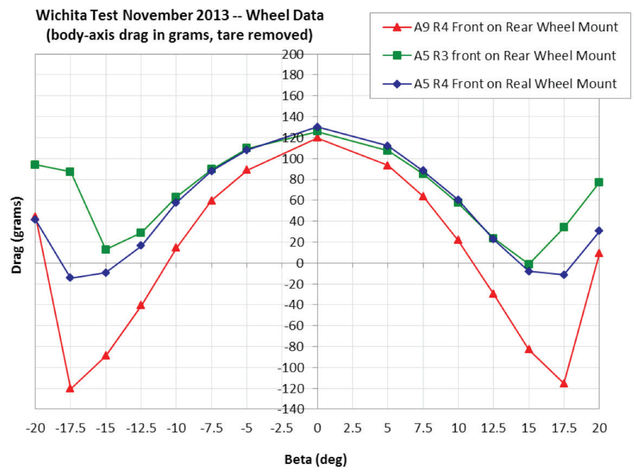


WSU VS. BENCHMARK

Between years 2012-2013, Trek conducted a series of tests to benchmark and establish the testing protocol at Wichita State University tunnel. The benchmarking effort involved comparing results of wheel tests, road bike tests, and TT bike tests from WSU tunnel against those from San Diego Low Speed Tunnel, and others.

Figure 24 compares the drag vs. yaw plot for wheel-only test conducted at Wichita State University vs. San Diego Wind Tunnel. Bontrager's Aeolus 9 clincher with R4 Aero tire, Aeolus 5 clincher with R3 tire, and Aeolus 5 clincher with R4 Aero tire were tested at both facilities. Inflation pressure of the tires were carefully monitored and noted and held the same for both testing, and the same wheels and tires were used. Although there's a slight difference in the absolute magnitudes of corresponding curves, the general yawing trend and ranking of the wheels prove to be in a good agreement between the two tunnels.





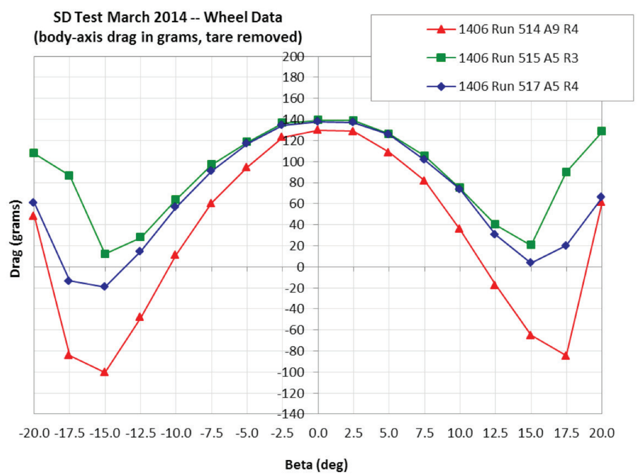


FIGURE 24

Drag vs. yaw result of the wheel-only bench marking test. Output from Wichita tunnel (above), and output from the San Diego tunnel (below)