REAP

TRIATHLON BIKE AERODYNAMIC DEVELOPMENT PAPER

VERSION110

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CONTENTS

1. EXECUTIVE SUMMARY

Reap has designed and built the world's fastest and most effective triathlon bike. It combines class-leading aerodynamics with highly refined comfort and geometry to enable athletes to perform at their best.

We achieved this by using an unprecedented combination of development and evaluation tools – CFD, wind tunnel and velodrome – to design, refine, evaluate and cross-validate our concept. Each of these tools in isolation is potent yet unable to give a complete picture.

By combining them we have been able to develop a new class-leading bike and prove its performance with data from the controlled environment of the wind tunnel and measured ride testing in a velodrome.

2. INTRODUCTION

Reap is a new British manufacturer specialising in ultra-high performance triathlon, time trial and road bikes. Our team has decades of carbon fibre engineering experience from aerospace, Formula One and the automotive industry, plus many years of triathlon and cycle racing at elite level.

Reap was established with the vision of returning high-end bicycle manufacturing to the UK and delivering class-leading performance, not only in terms of wind tunnel proven aerodynamics but also the comfort and rideability that are essential for an athlete to achieve their best results. We spent over two years developing our triathlon bike, taking a 360-degree approach that carefully examined every aspect of performance and drew upon all available R&D tools.

Our process began with in-house conceptualisation before taking refined CAD iterations to leading Computational Fluid Dynamics (CFD) experts TotalSim - who consulted for UK Sport on the Team GB Olympic bikes – for detailed study in a virtual environment. A selection of prototypes were built and tested both in a wind tunnel and in a velodrome against the leading competitor. This paper details the complete development process.

Throughout the entire process Reap has focused on using the best of British technology and engineering, be that our in-house engineers and aerodynamicists, or outsourcing to TotalSim for our CFD, Southampton University for our wind tunnel testing, Derby Velodrome for our live aerodynamic tests, and top UK athletes Harry Wiltshire and Kevin Dawson as our test pilots.

3. PROJECT OBJECTIVES

- To produce a world-class triathlon bike
- To empower the athlete to perform to the best of their abilities, with a bike that provides the most aerodynamic, comfortable and adaptable solution.

4.1 CONCEPTS

The concept phase was driven by a desire to create a bike that provided the comfort and aerodynamics of beam bikes such as the Zipp 2001 and Lotus Type 108 while bringing them into the 21st century with an updated, stylish design that incorporates the latest in technology and component integration.

A beam frame uses the strengths of carbon fibre to remove elements of traditional diamond frames, the design of which is dictated by the characteristics of the steel tubes used since that frame type originated over a century ago. Rather than making a steel bike out of carbon fibre tubes, as per many conventional road bikes today, a beam design such as the Reap makes the most of what a carbon fibre monocoque can offer. Eliminating the seatstays and seat-tube removes those elements from the airflow to instantly reduce drag. It also creates the 'beam' look of the bike and allows the toptube to provide greater compliance. Through advanced carbon fibre engineering, this minimal structure can retain incredibly high torsional rigidity for precise handling and efficient power transfer.

A selection of the original concept sketches is shown below. You can see the same design ethos running through them all. These concepts evolved as we developed our geometry; ideas were evolved to optimise hydration, fit, adjustment and integration.

The Reap team threw the design rulebook out of the window and instead approached the design with an open mind and made informed decisions around each element. The bike was designed in CAD and went through multiple phases of internal optimisation and development before continuing on to CFD.

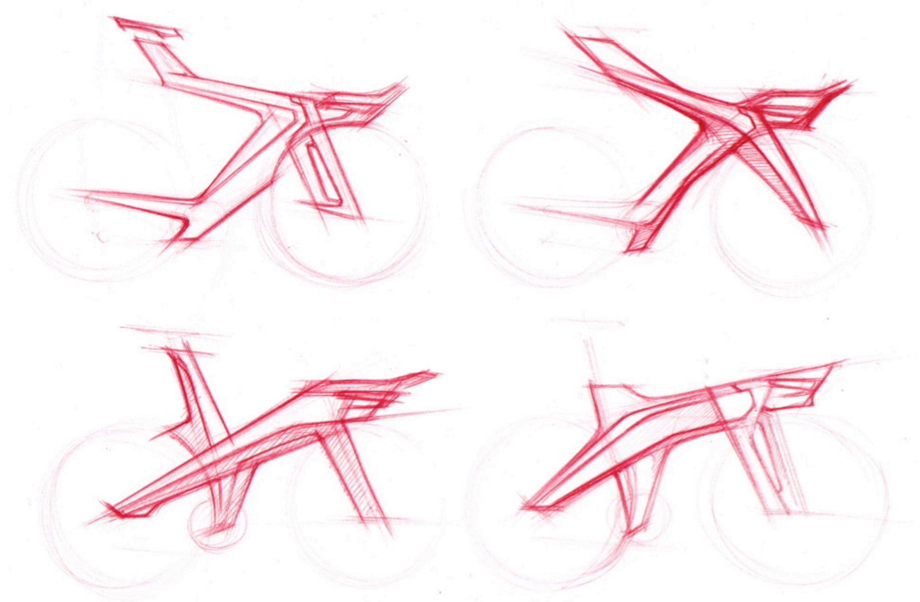


Figure 1 - Concept Sketches

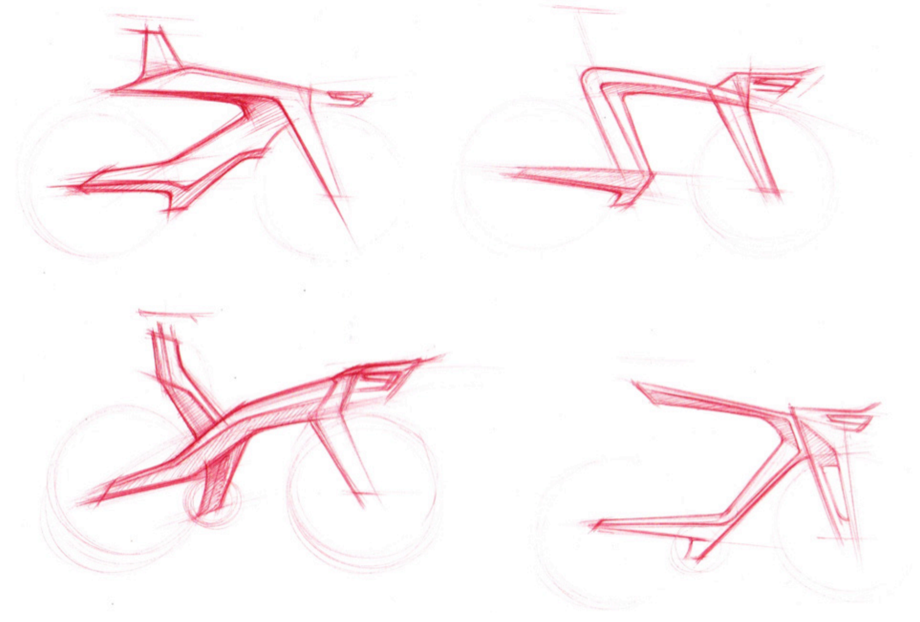


Figure 2 - Concept Sketches

4.2 CFD EVALUATION

Computational Fluid Dynamics (CFD) was used to drive development of the CAD models, allowing a thorough understanding of the flow structures and drag forces experienced by all areas of the bike. CFD uses numerical analysis to simulate and analyse the airflow around an object in a virtual environment. Reap employed TotalSim to perform all of the CFD analysis. Although this could have been performed in-house, TotalSim have an incredible wealth of experience in bicycle design and aerodynamics. They have been involved in the development of many world-class bikes including the multiple Olympic medal-winning UKSI bike used by the Great Britain Track Cycling Team.

TotalSim used their best practice of bicycle aerodynamic analysis. The bike was analysed with a rider, utilising a full body scan of our test pilot, professional Ironman athlete Harry Wiltshire. All cases were run with a rolling road and rotating wheels matched to the air velocity. Wheels were run without spokes and therefore the wheels were considered as moving walls with a given angular velocity. All cases were run in two crosswind configurations: 0.5 degrees and 10.0 degrees. Longitudinal flow velocity was increased at yaw so that velocity in the bicycle’s X-axis was kept constant for both conditions. Detached Eddy Simulation was used to transiently simulate the flow. Forces and airflow were solved in time and averaged over the final second of simulation time. These time averaged forces and fluid flows are what has been used for all graphs and discussion throughout this report.

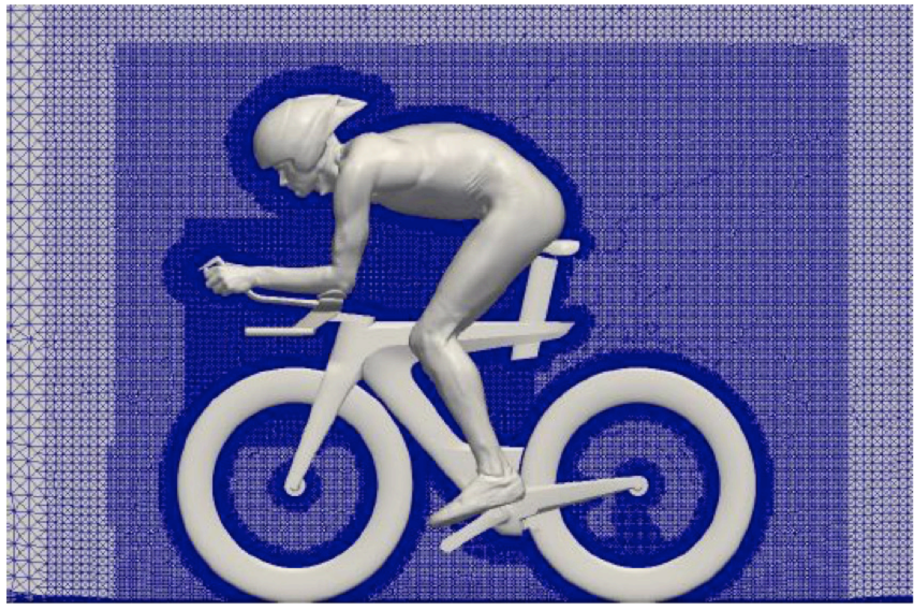


Figure 3 - Volume Mesh

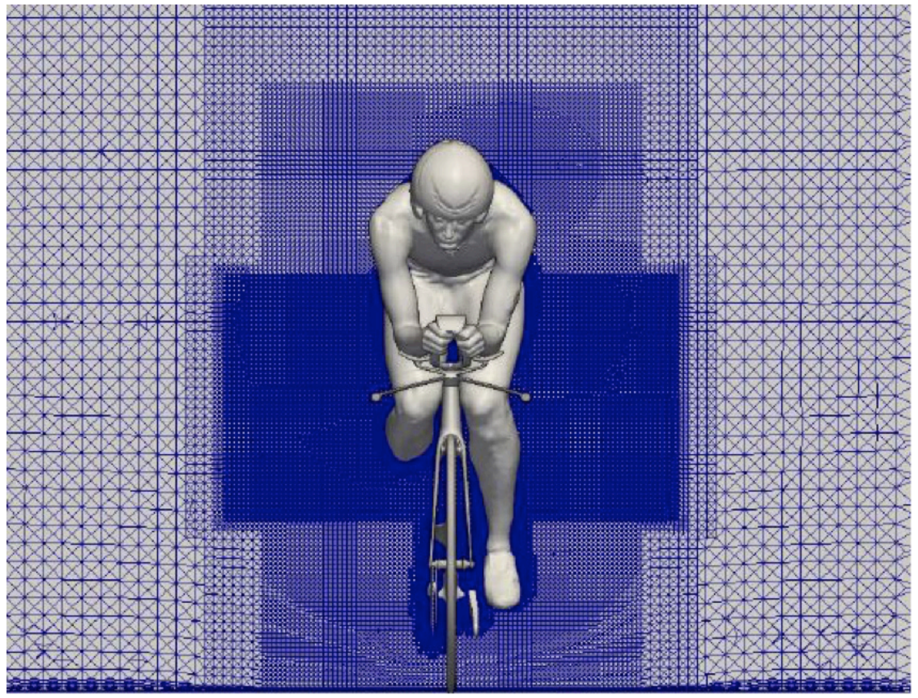


Figure 4 - Volume Mesh

In order to better analyse the bike, the geometry was separated into separate parts. These are:

- Frame
- Saddle
- Fork
- Handlebar
- Front wheel
- Rear wheel
- Gears and groupset
- Rider – Torso
- Rider – Legs
- Rider – Arms
- Rider – Helmet & Head
- Rider – Shoes

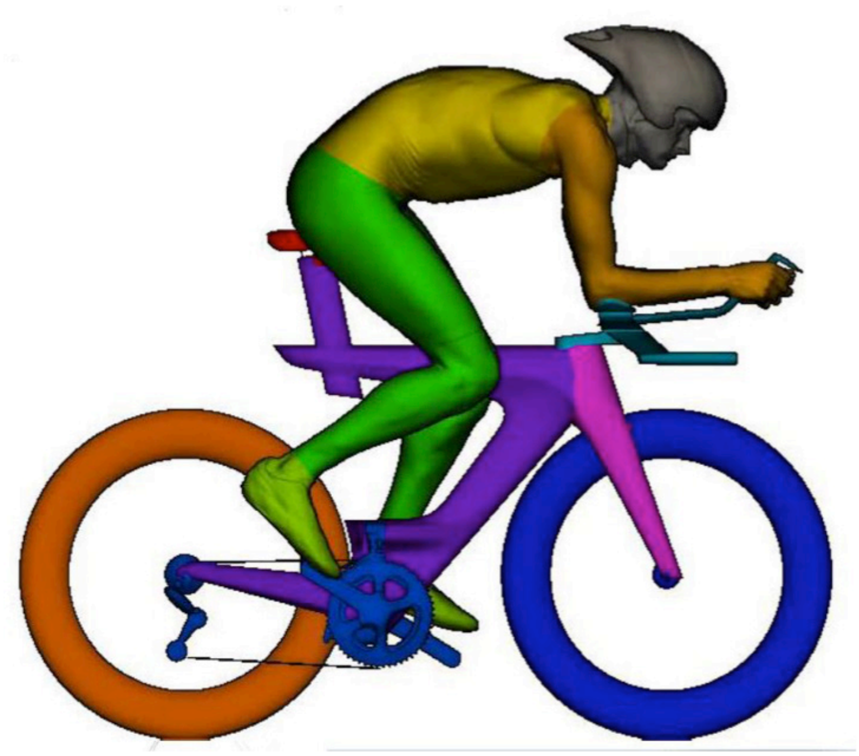


Figure 5 - Segregated Bike Geometry

By separating out the bike and rider geometrically, we could objectively analyse drag sources and their relative contributions, as well as quickly highlighting areas that would provide the most improvement. This separation allowed Reap engineers to spend their time productively, generating ideas that would create large reductions in drag.

4.2.1 TEST CYCLE RESULTS 1

The first cycle of tests from TotalSim were aimed at identifying areas of separation and messy flow. Separation and messy flow are relatively low hanging fruit in the world of aerodynamics as they contribute significant drag to the bicycle but can easily be resolved with careful and considerate design.

The baseline CFD drag force results are shown in the four pie charts below. These show the drag sources, absolute aerodynamic wattage values and proportion of total drag.

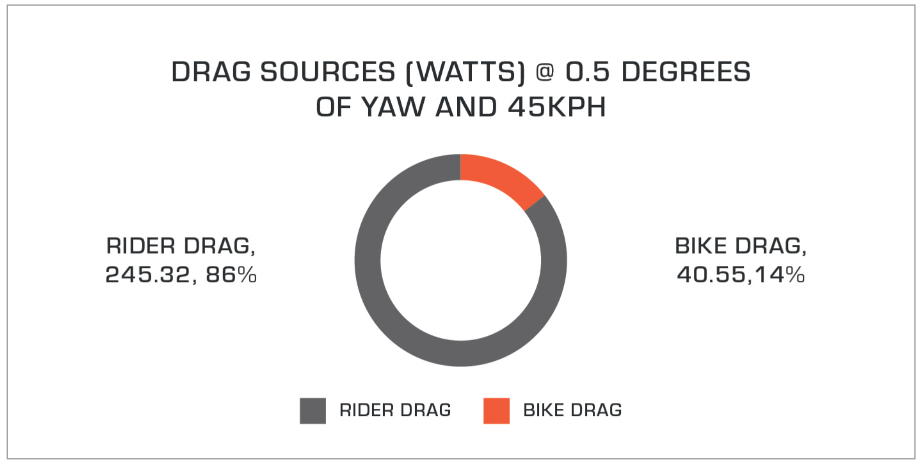


Figure 6 - Drag Sources @ 0.5 Degrees & 45kph

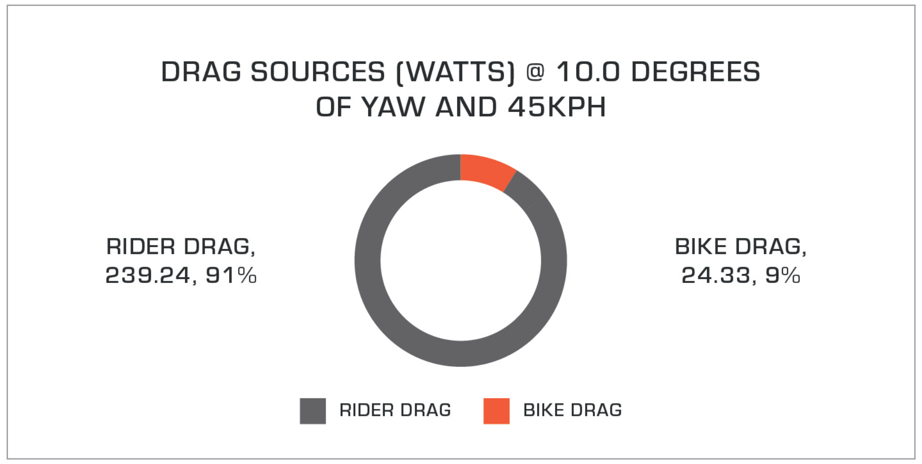


Figure 7 - Drag Sources @ 10.0 Degrees & 45kph

It is clear to see that the largest proportion of drag comes from the rider. This is no surprise due to the sheer size and the bluff body shape of the rider. This demonstrates why Reap has always been heavily focused on creating geometry and a range of fit that allows the rider to adopt their most aerodynamic position with ease.

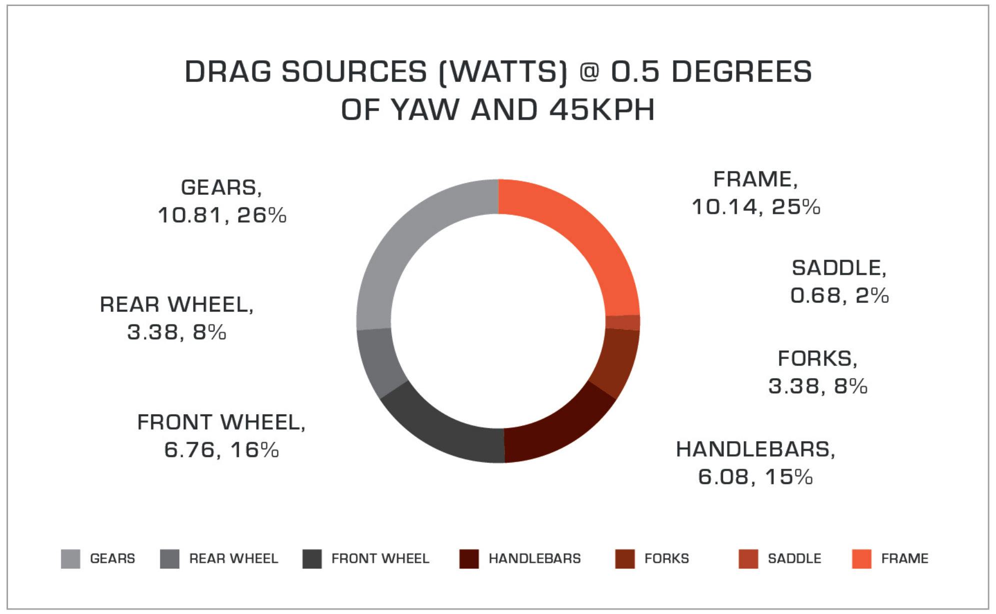


Figure 8 - Drag Sources. 0.5 Degrees yaw @ 45kph

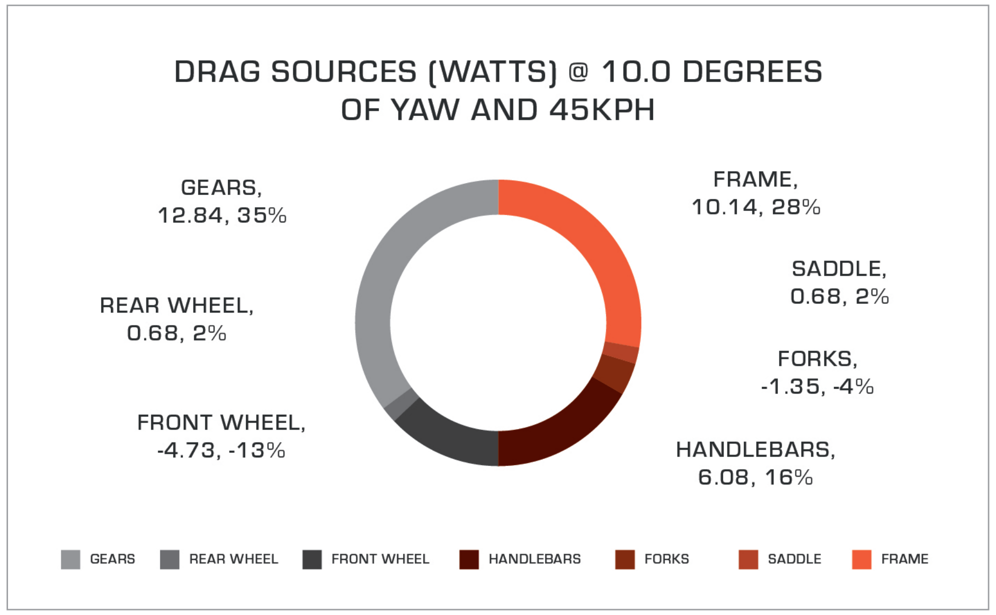


Figure 9 - Drag Sources. 10.0 Degrees yaw @ 45kph

Breaking down drag to each area of the bike, the two main drag sources are the frame and the drivetrain. This is due to the size of the frame relative to other components and how it has to deal with the flow over multiple different areas of the bike. The drivetrain might be small but each component is geometrically complex and designed with function in mind, not aerodynamics. A unique design employed by Reap is the blended downtube that creates a clean leading edge ahead of the front derailleur. This reduces the drag created by the front derailleur by almost 50%. Behind these two, the front wheel and the handlebar are the next two largest drag sources. Both experience clean airflow and therefore have to manage this flow well to avoid large pressure wakes.

The CFD test results gave good direction on where the team's focus should be, as well as providing great detail on what areas are suffering from separated or messy flow. These are detailed below as well as the processes taken to resolve the issues.

A very clear area of slightly separated flow was identified on the lower downtube near the bottom bracket, shown in the following two figures. This was caused by a feature line extending from the chainstays and bottom bracket through to the lower section of the downtube. This was modified in CAD ahead of the second CFD test cycle.

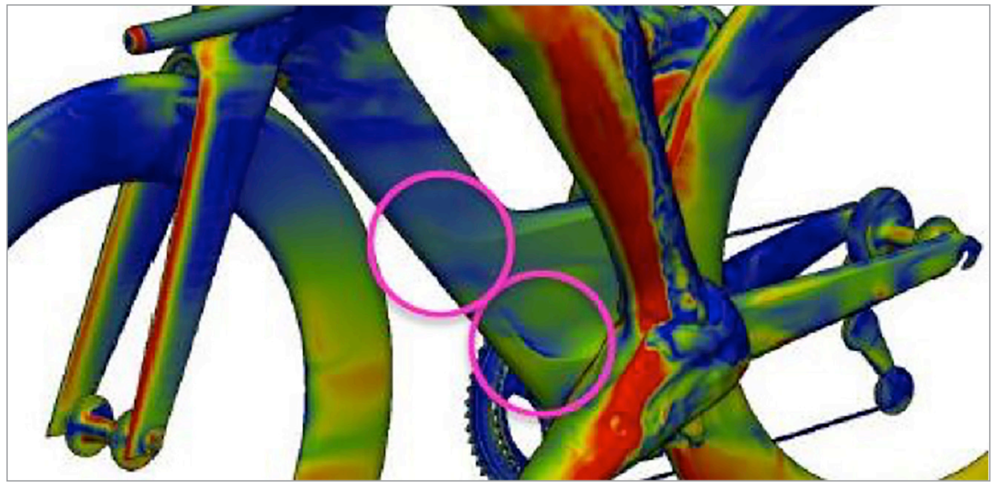


Figure 10 - Downtube Near Wall Velocity Magnitude

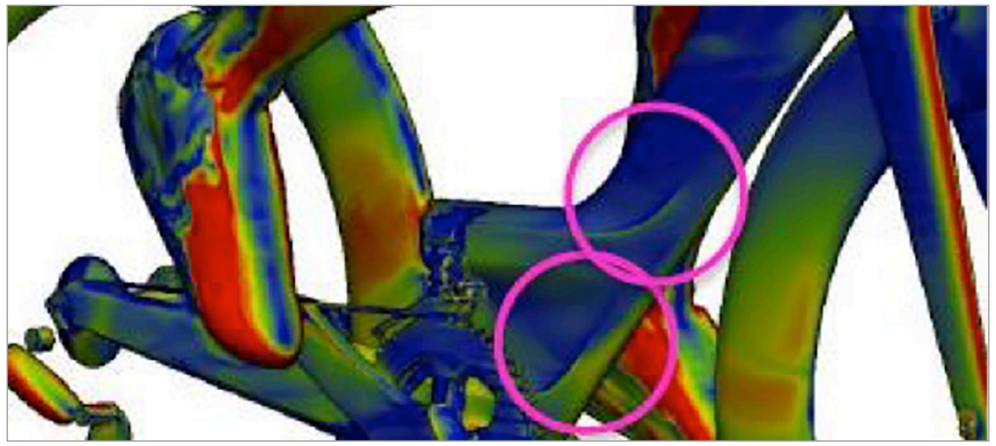


Figure 11 - Downtube Near Wall Velocity Magnitude

There was a large volume of separation around the fork crown and headtube. The second area of clear separation had two causes. The geometry leading off the headtube and fork crown had a large rearward facing step, as seen in the figures below. However, this was also combining with dirty air stemming from a blockage around the brake calliper and pads, shown in Figure 13.

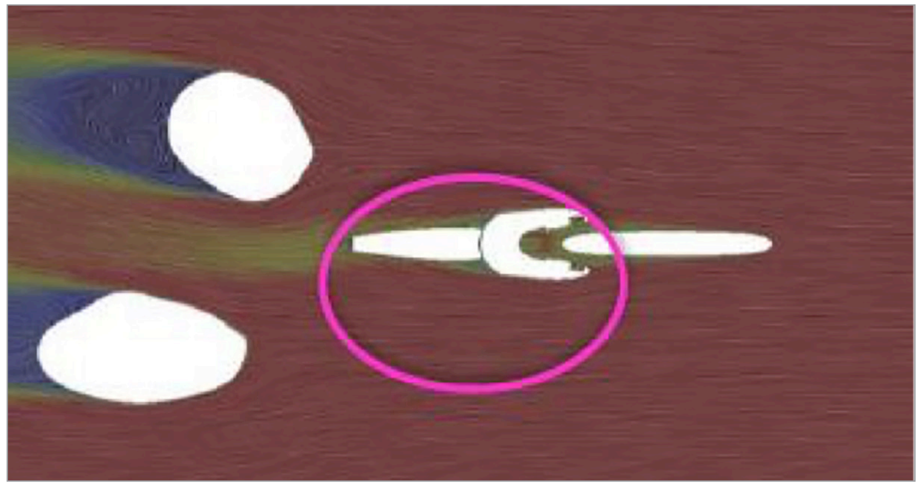


Figure 12 - Fork Crown Separation

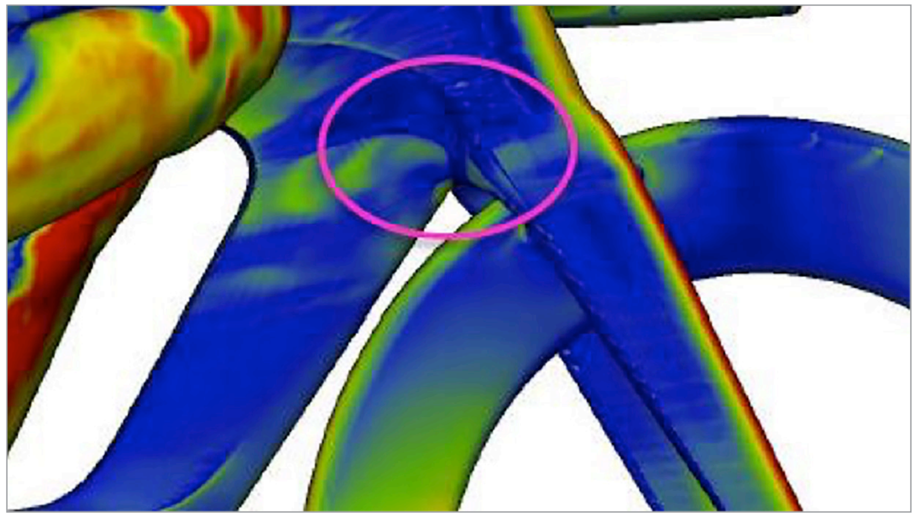


Figure 13 - Fork Crown Separation

Figures 13 and 14 showing how the geometry around the fork crown and fork changed to reduce the blockage and also the rearward step that was causing the flow to separate.

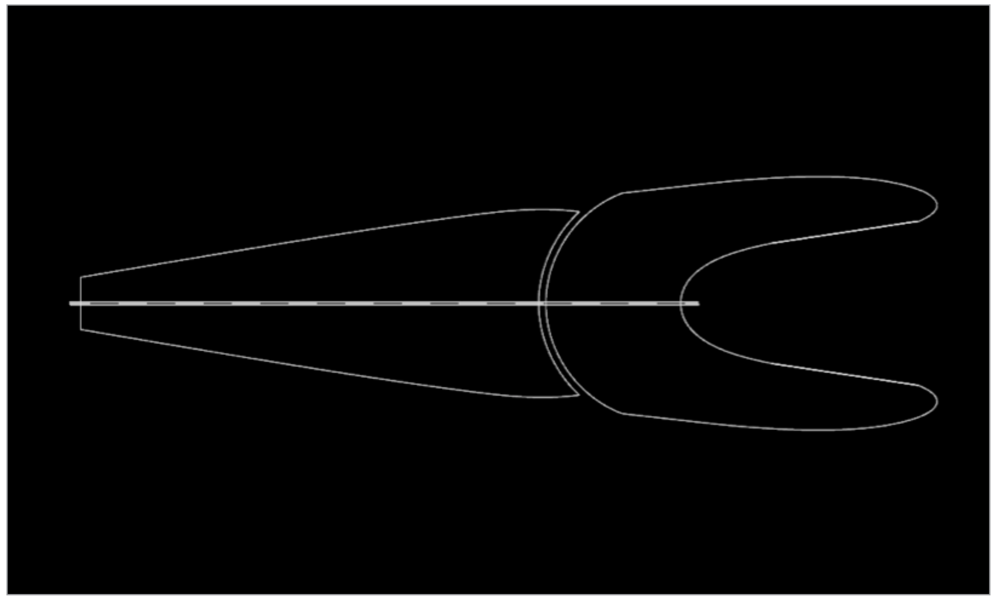


Figure 14 - Original Fork Crown

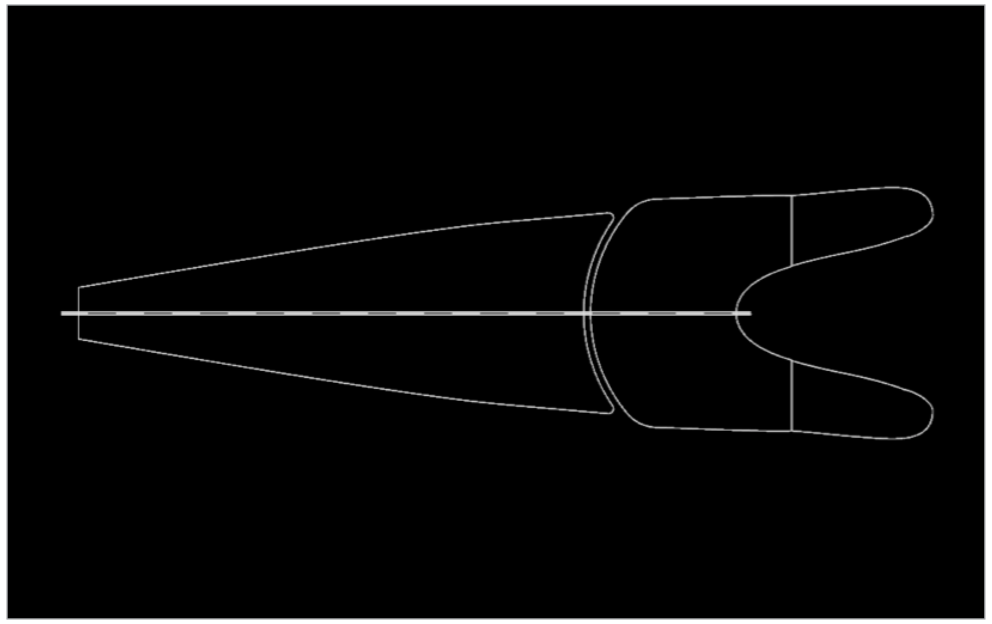


Figure 15 - New Fork Crown

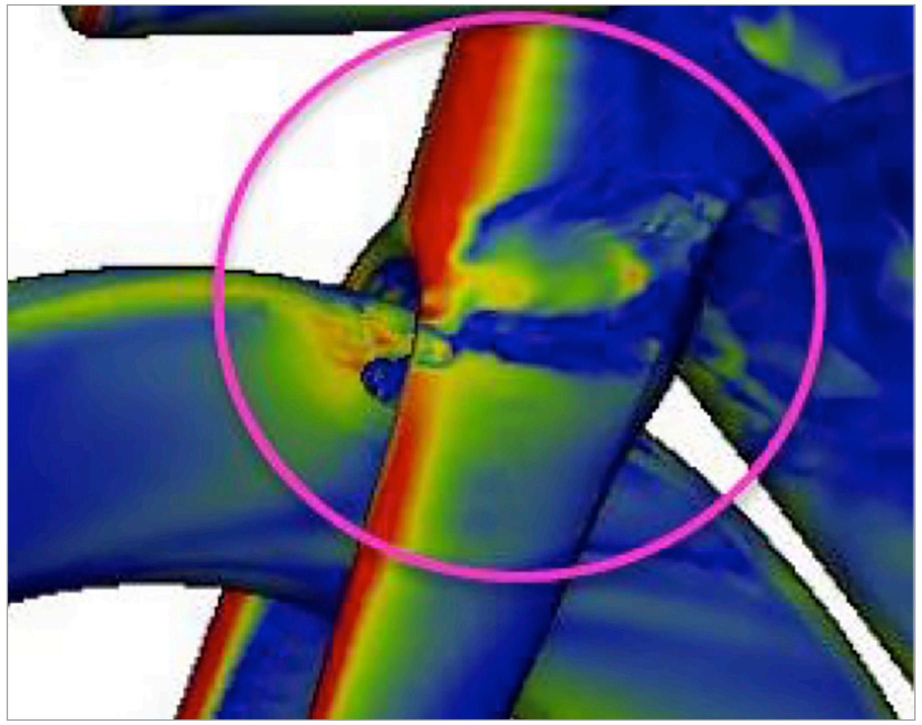


Figure 16 - Brake Pad Messy Flow

The blockage around the brake calliper area required a rethink of the geometry in order to properly address the blockage and allow air to flow through and around the fork and calliper area. The CFD also highlighted a small area of low energy flow around the fork profile's trailing edge, lower down the fork. To optimise both situations the fork geometry was significantly modified. The second CFD test cycle was entered with new designs for the fork profile, fork crown and headtube.

4.2.2 TEST CYCLE RESULTS 2

The drag results from the second test cycle are shown below. On the whole a net reduction in drag was seen, especially from the frame where significant work had gone into cleaning up the headtube and downtube. However, the fork drag has increased, notably at high yaw.

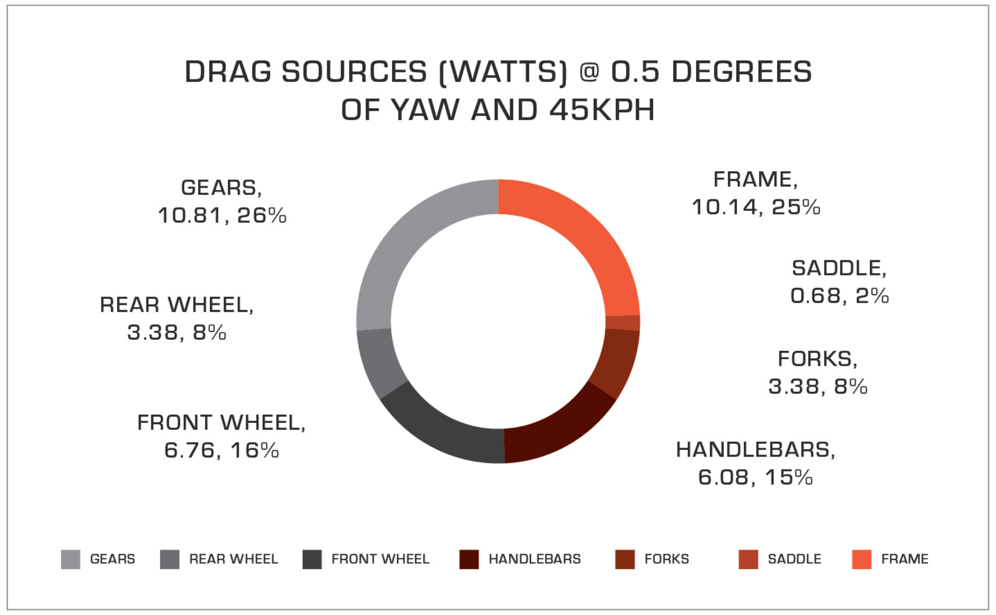


Figure 17 - CFD Cycle 2 - Drag Sources 0.5 Degrees

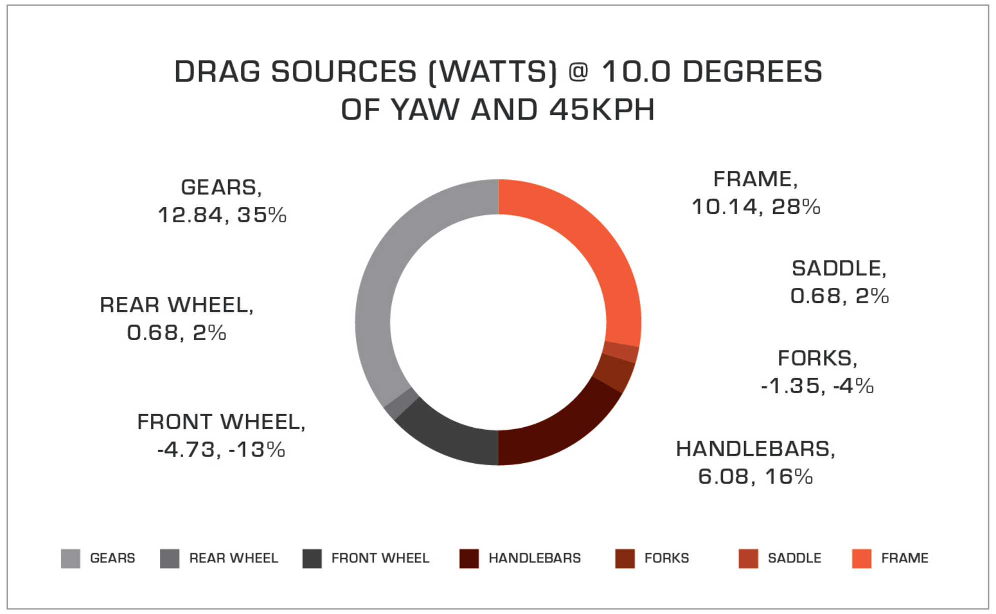


Figure 18- CFD Cycle 2 - Drag Sources 10.0 Degrees

When analysing the source of the fork drag, it is clear the newer profile was performing poorly due to the large trailing edge, especially at high yaw. The fork had been brought closer to the wheel, which typically improves low yaw performance at the expense of high yaw performance. A rethink of the profile as well as widening the fork stance negated these losses, providing a more stable flow structure at high yaw and minimal low pressure wake.

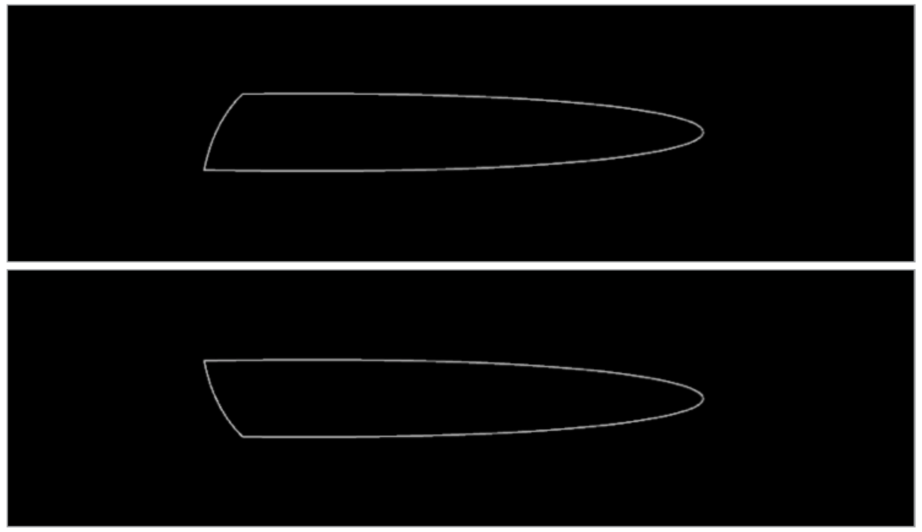


Figure 19 - Fork Profile Version 1

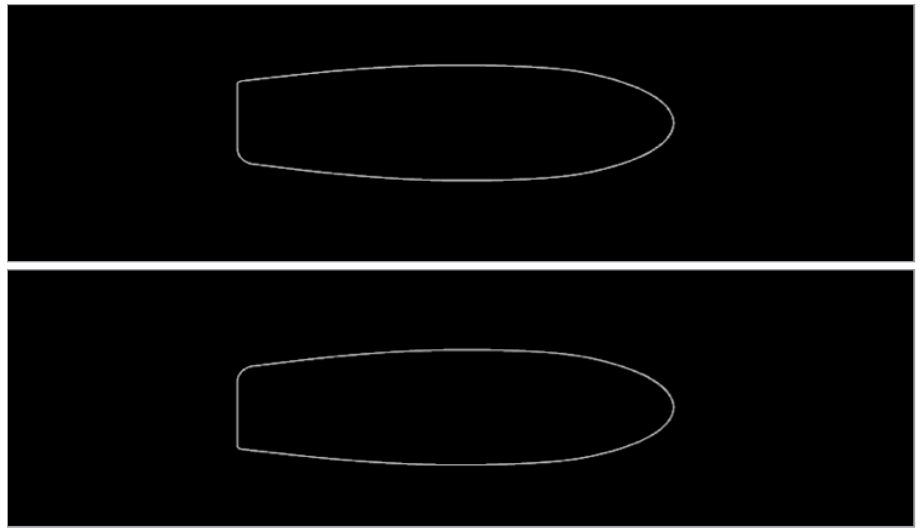


Figure 20 - Fork Profile Version 2

TotalSim also noted many areas of untidy flow structures around the concept handlebar and stem. After discussion among the design team, it was decided to revert back to a standard stem and handlebar design. The advantage was twofold. Firstly, it removed any proprietary hardware and opened up the option of using any commercially available stem and bar set-up, allowing customers to select the option that best suited their position, geometry and budget. Secondly, it allowed the design team to focus their time on the frame. The figure below shows how the stem arrangement changed to allow a standard stem to fit cleanly and also allow a broad range of stack height adjustment.

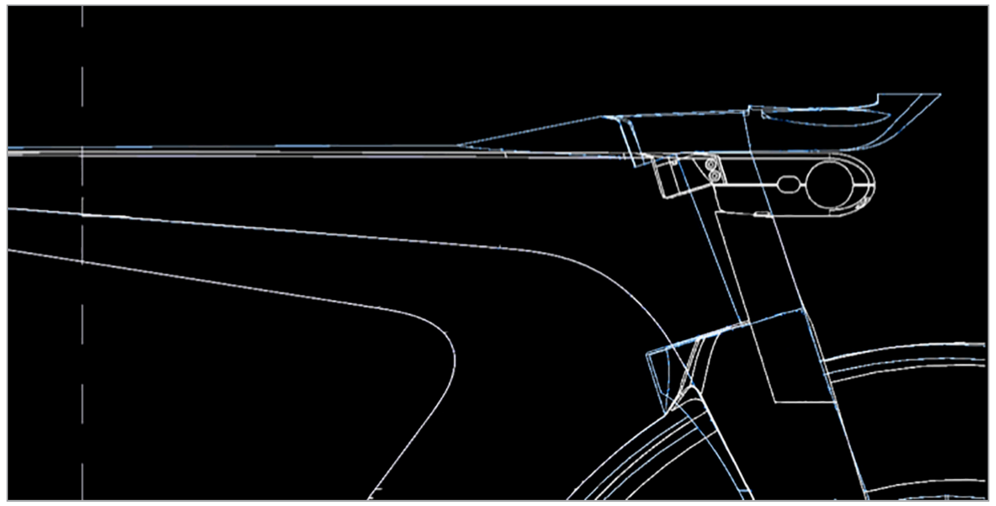


Figure 21 - Modified Stem Geometry

The modified stem arrangement allows a much lower stack and the use of any commercially available handlebar system. It also slightly reduces the frontal area and levels the stem in line with the toptube, which CFD had highlighted as a lossy area with scope for improvement.

CFD had provided invaluable insight into the flow structures experienced across the entire bike, allowing Reap to improve the aerodynamic performance and gain understanding of how to design even faster bikes and components.

4.3 WIND TUNNEL TESTING

To further validate and compare the performance of the Reap bike, the team took the bike, along with test rider Harry Wiltshire, to the R.J. Mitchell Wind Tunnel at Southampton University. The primary aim was to assess the aerodynamic performance of the prototype bike, then to also investigate and adapt certain aspects. We also took along the current leading triathlon bike on the market, the Cervélo P5-Six, to compare and collect data for further comparison.

Prior to the test Reap had spent considerable time analysing triathlon and time trial bike courses worldwide to calculate the yaw angles and velocities actually experienced by athletes, and for how long these conditions were experienced. The conclusion of this study was that it’s very rare for athletes to experience yaw above 10 degrees and when they do it is for an incredibly short time period. The velocity range calculated was broad and highly dependent on the course and rider. This analysis led us to plan a yaw sweep from 0 to 12.5 degrees in increments of 2.5 degrees, with each yaw angle tested at 8, 10, 12 and 14 m/s air speed (29kph, 36kph, 43kph and 50kph).

Each bike was built to be as near to identical as possible, with the same frame size, wheels (Zipp 404/808 Firecrest), tyres (Continental GP4000sII), groupset (Shimano Ultegra Di2), crank position, gear position, saddle height and saddle position. This was done to ensure any delta between the bikes was purely down to the frames and not the components.

The only major difference was the handlebar set-up. The Cervélo P5-Six was built up with the proprietary Cervélo-3T integrated handlebars. The Reap tri bike was built with an unbranded TT cockpit, shown below.

Figure 22 - Handlebars Fitted to Reap TT Bike

The test map was run for three different set-ups: Reap TT bike, Cervélo P5-Six and an early prototype of the forthcoming Reap road bike. Data was collected without a rider, due to the inaccuracies and variation created by using a human test rider – even if the rider stays completely still their breathing effects the shape of their torso and therefore the airflow. In future testing, we are planning to use a mannequin in order to create a perfectly repeatable test protocol that also addresses the rider's interaction with the bike.

Tares were taken before and after each test run and averaged across both. These, along with the strut tares, were subtracted from the test data.

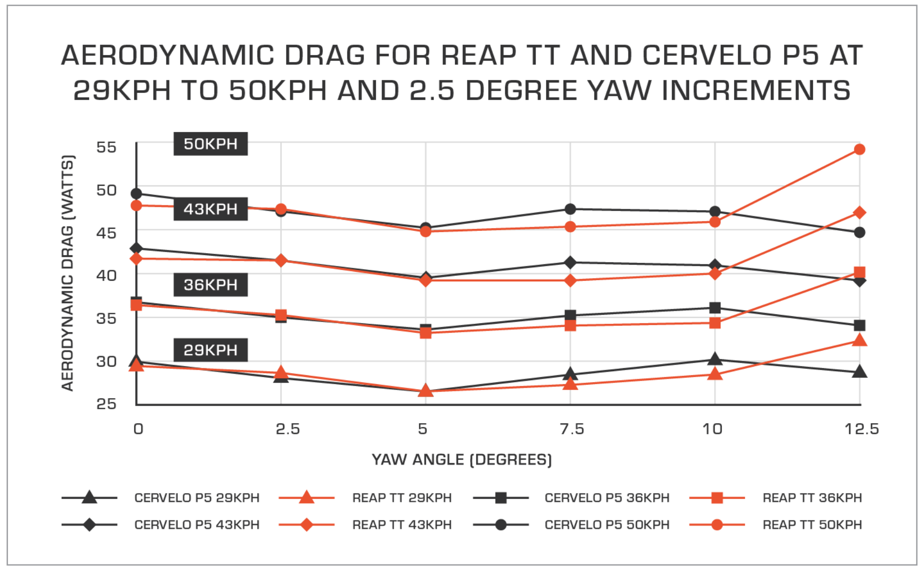


Figure 23 - Aerodynamic Drag against Yaw

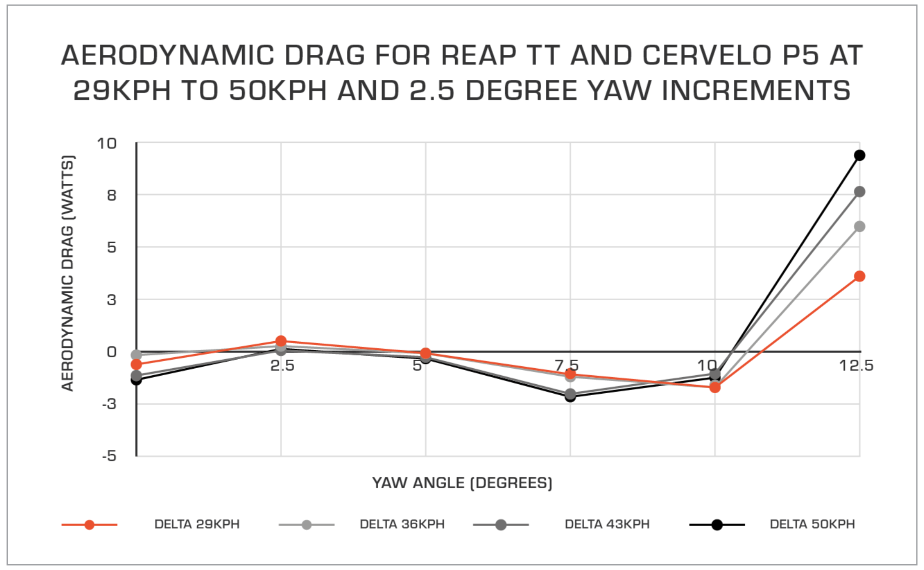


Figure 24 - Aerodynamic Drag Delta

The first cycle of tests from TotalSim were aimed at identifying areas of separation and messy flow. Separation and messy flow are relatively low hanging fruit in the world of aerodynamics as they contribute significant drag to the bicycle but can easily be resolved with careful and considerate design.

The baseline CFD drag force results are shown in the four pie charts below. These show the drag sources, absolute aerodynamic wattage values and proportion of total drag.

4.4 PRODUCT TESTING & STRUCTURAL REFINEMENT

In order to properly evaluate the prototype design, Reap took top UK cyclist, time triallist and triathlete, Kevin Dawson, to Majorca to perform a comprehensive range of tests. Kevin Dawson won the British Best All Rounder a record 11 times, held the UK 100-Mile TT Competition Record for 12 years and has an impressive road palmarès. The test protocols were broad and designed to encompass as many areas of bike handling as possible. They included repeated hill climb efforts, both seated and standing, as well as high-speed descents and windy, exposed flat roads. All of these rides were structured to replicate what would be experienced by a triathlete during a typical triathlon bike course. The Reap team followed Kevin Dawson during the testing to help analyse the results throughout the day as well as make bike and equipment adjustments.

From this structured week of testing a number of areas for improvement were discovered. The main issue was that during high-speed descending there was a noticeable disconnect between the front and rear ends of the bike. The team performed multiple test runs through a range of switchbacks and isolated the issue to the downtube stiffness. Back at the factory, we developed a new carbon fibre lay-up structure that significantly improved the downtube stiffness, especially under torsion as experienced in switchback cornering. Testing since this change has shown that this issue has been resolved entirely.

4.5 VELODROME TESTING

In order to gain real-world data, aerodynamic testing was performed at Derby Velodrome.

This test had multiple objectives:

- Gather real-world performance data on the Reap TT bike
- Compare the performance of the Reap TT bike to the Cervélo P5-Six in a live environment
- Test and develop a range of hydration and storage options
- Assess the aerodynamic performance of multiple positions for Reap test pilot Harry Wiltshire ahead of his 2017 Ironman campaign

Velodrome aerodynamic testing is very simple to perform but requires precise control of variables to minimise errors and to maintain high data quality. Each test run was performed at 45kph for approximately four minutes on a clear and empty velodrome. Data was collected using a crank-based power meter. Air density was calculated for each test run from ambient air temperature, air pressure and humidity. System mass was measured prior to each test run. The rolling resistance coefficient (Crr) was measured on rollers using the Tom Anhalt roller method. The drivetrain was kept in the same gear for each run to maintain constant drivetrain efficiency across all runs. The same power meter and bottom bracket were used on both the Reap and the Cervélo, again to keep everything consistent.

The data from each test run was processed in MatLab, using an energy balancing equation of motion in order to calculate the instantaneous CdA for each second of the test run. This was then averaged across the entire test run to give a CdA value for that particular set-up. The results are shown below, comparing the performance of the Reap and Cervélo P5-Six, with no bottles or storage and with two bottles behind the saddle along with either a traditional between-the-arms (BTA) bottle set-up (Cervélo) or a proprietary, aero, extension-mounted set-up (Reap).

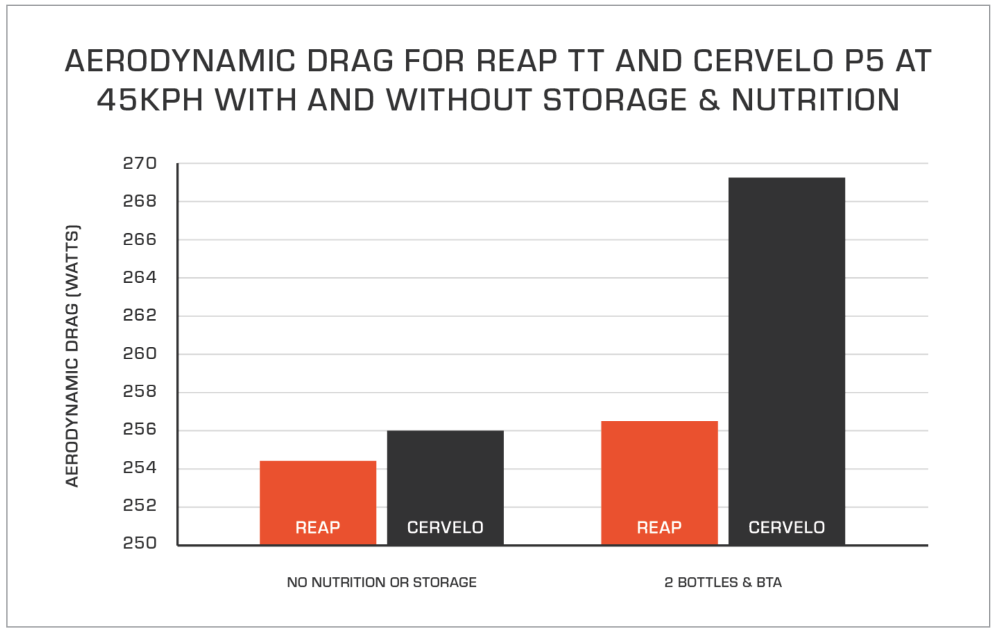


Figure 25 - Total Aerodynamic Drag for Reap & Cervélo @ 45kph

The velodrome testing confirmed the wind tunnel test results in that the Reap bike outperforms the Cervélo P5-Six. The exciting result for athletes is that with two bottles fitted behind the rider and a BTA system, the Reap bike was 13W faster at 45kph. The Cervélo P5-Six BTA was a standard round bottle mounted horizontally between the rider's arms. The Reap BTA was a prototype, aerodynamic profiled bottle, mounting between the two extensions and attaching to the headtube.

4.6 PERFORMANCE BENEFITS

The Reap bike offers clear performance benefits for any triathlete aiming to maximise their performance on the bike. The Reap bike is significantly more aerodynamic than the leading competitor when in a full race set-up.

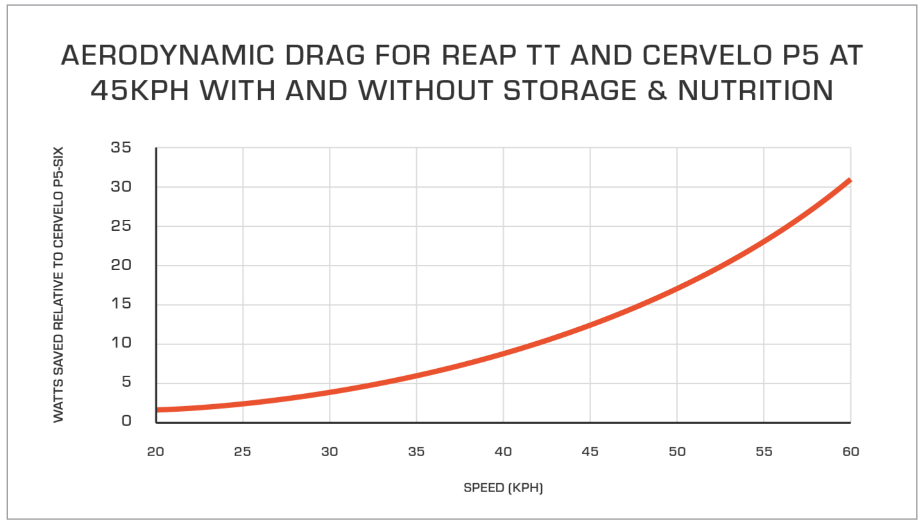


Figure 26 - Aerodynamic Watts Saved for Reap Versus Cervélo P5-Six

We have calculated the time savings that could be expected by athletes on a range of Ironman and Challenge courses worldwide, targeting from four to seven hours for the bike course. The data has been calculated for a 75kg rider, with good quality race tyres (0.004 Crr), good bike handling/descending skills and experiencing typical atmospheric conditions for that given course.

FIGURE 27 ON THE FOLLOWING PAGE

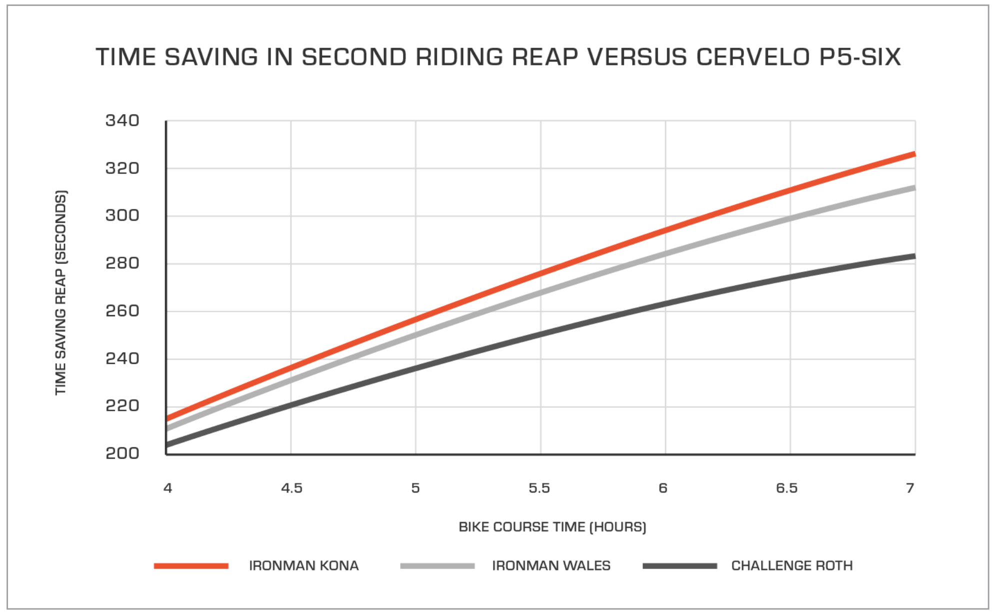


Figure 27 - Time Saving

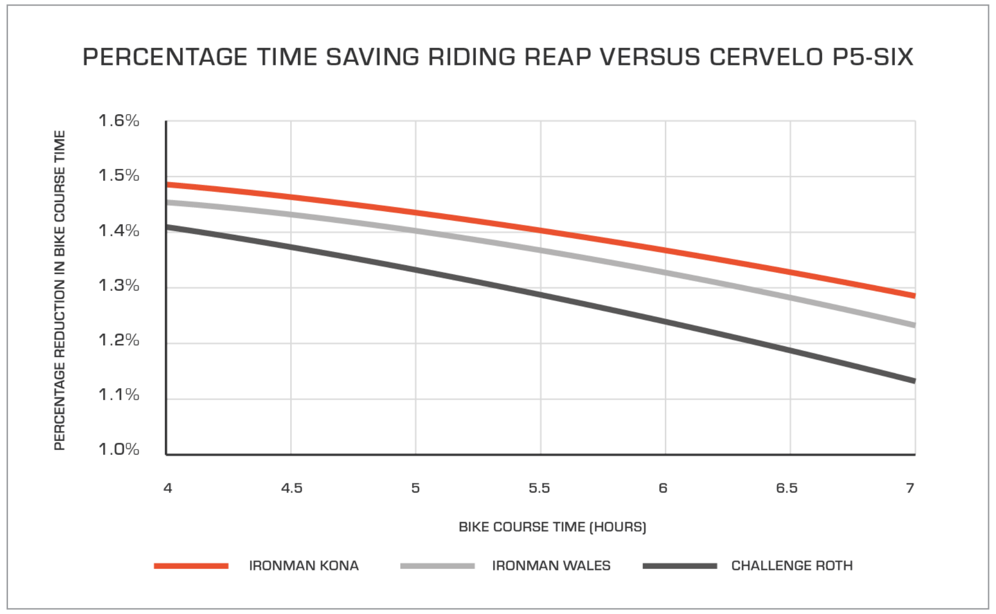


Figure 28 - Percentage Time Saving

As can be seen, the pure time benefits of the Reap bike are huge, with all riders achieving over a three-minute saving no matter what course and time they are riding.

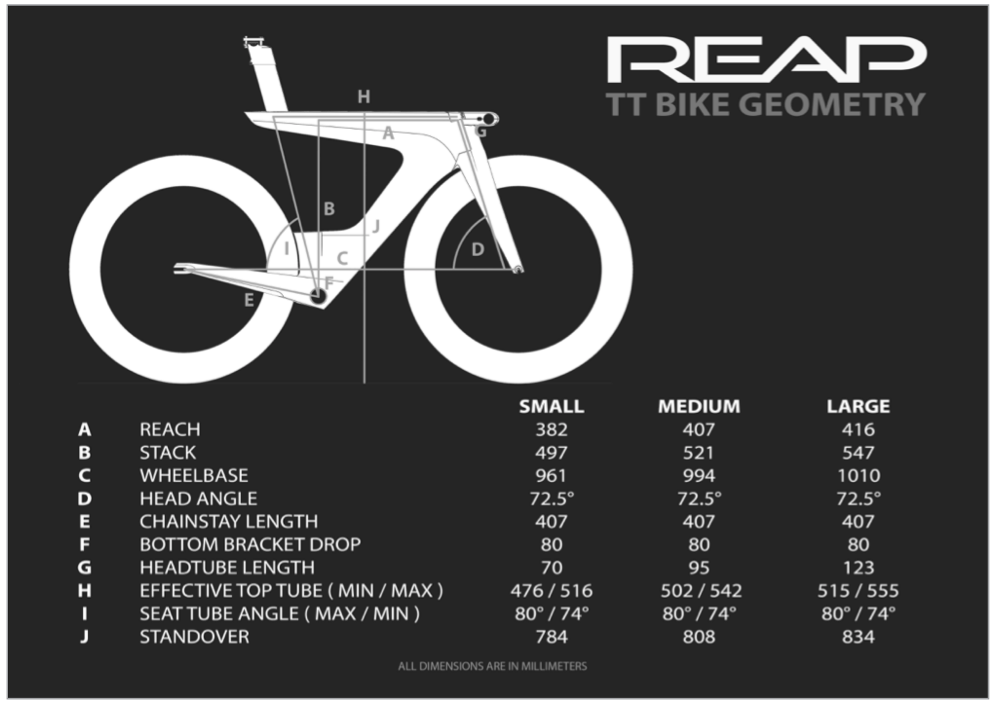
5. FUTURE DEVELOPMENTS

Reap is currently developing an integrated hydration system and aero cockpit to suit this system. Throughout the development process, we have been working on our own unique aerobar system that combines ultimate adjustability with aerodynamics to match that of the Reap bike. The recent velodrome aero test of Reap's prototype hydration system showed huge potential, with a very small aerodynamic performance deficit for running the system. Reap are now pressing on with integrating this hydration system with their aero bar to create a unique and high performance package.

6. CONCLUSION

The Reap bike has been developed from the start with the rider in mind, employing the best that British engineering has to offer. Throughout many design cycles, the bike has been optimised and refined to become the class leader that it is now. The final velodrome sign-off test has shown the true pedigree this bike has and we fully expect this to be realised on the 2017 Ironman circuit.

7. FINAL GEOMETRY



		SMALL	MEDIUM	LARGE
A	REACH	382	407	416
B	STACK	497	521	547
C	WHEELBASE	961	994	1010
D	HEAD ANGLE	72.5°	72.5°	72.5°
E	CHAINSTAY LENGTH	407	407	407
F	BOTTOM BRACKET DROP	80	80	80
G	HEADTUBE LENGTH	70	95	123
H	EFFECTIVE TOP TUBE (MIN / MAX)	476 / 516	502 / 542	515 / 555
I	SEAT TUBE ANGLE (MAX / MIN)	80° / 74°	80° / 74°	80° / 74°
J	STANDOVER	784	808	834

ALL DIMENSIONS ARE IN MILLIMETERS

Figure 29 - Final Reap Geometry

8. RAW DATA

Yaw Angle	Calc Velocity	Total Drag	Bike Drag	Rider Drag
0.50	12.50	285.87	40.55	245.32
10.00	12.50	263.57	24.33	239.24

Figure 30 - CFD Bike & Rider

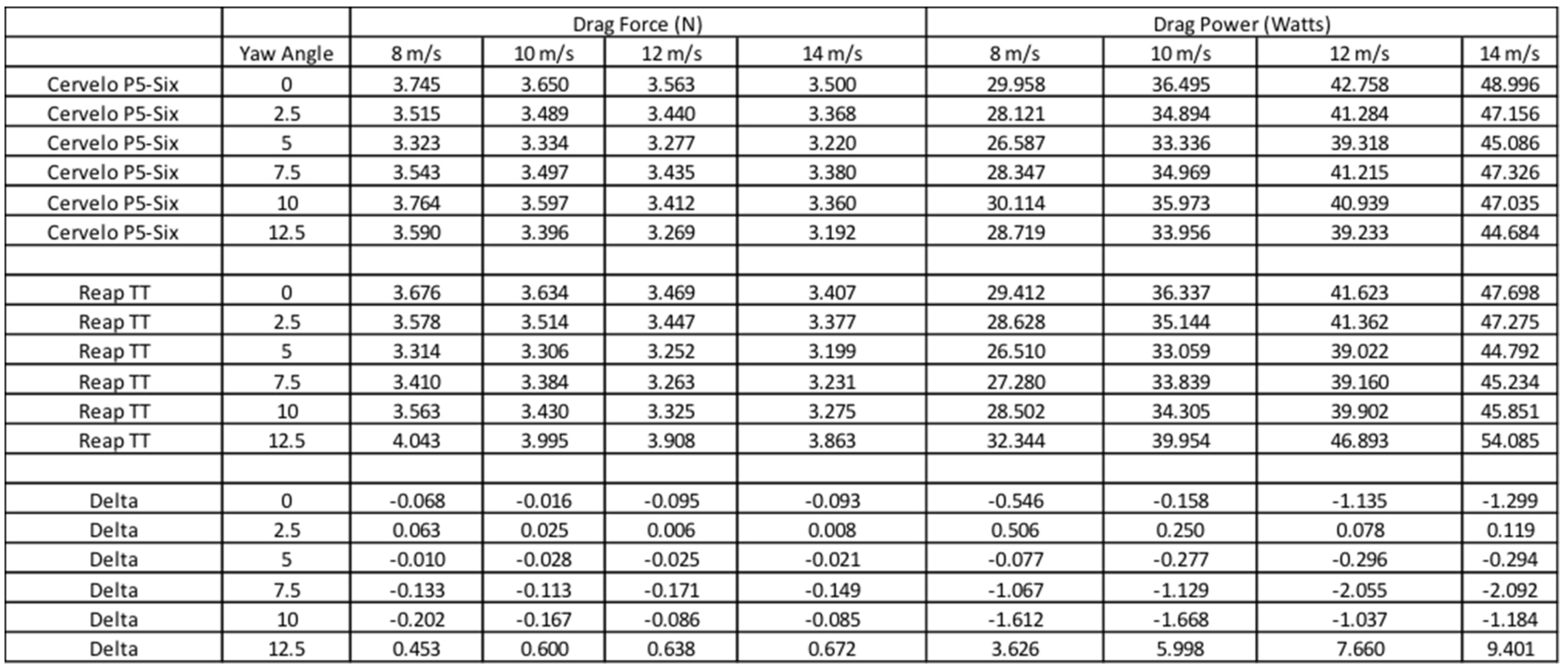
		Aerodynamic Drag in Watts @ 12.5m/s						
	Velocity	Frame	Saddle	Forks	Handlebars	Front Wheel	Rear Wheel	Gears
Test Cycle 1	12.5	9.867	0.473	3.244	5.812	7.029	3.649	10.746
	12.5	10.543	0.405	-1.149	6.488	-4.866	0.338	13.043
Test Cycle 2	12.5	9.124	0.405	3.582	5.677	7.096	3.785	10.610
	12.5	9.664	0.473	0.270	6.015	-4.866	0.270	13.111
Delta	0	-0.743	-0.068	0.338	-0.135	0.068	0.135	-0.135
	0	-0.879	0.068	1.419	-0.473	0.000	-0.068	0.068

Figure 31 - CFD Bike

	CdA (m^2)	Aerodynamic Drag (Watts)
Reap Bike. No Bottles or Storage	0.2202	254.59
Reap Bike. 2 bottles and BTA bottle system.	0.2218	256.51
Cervelo P5-Six. No Bottles or Storage.	0.2214	255.95
Cervelo P5-Six. 2 bottles and BTA bottle.	0.2329	269.29

Figure 32 - Velodrome, Reap & Cervélo

8. RAW DATA



		Drag Force (N)				Drag Power (Watts)			
	Yaw Angle	8 m/s	10 m/s	12 m/s	14 m/s	8 m/s	10 m/s	12 m/s	14 m/s
Cervelo P5-Six	0	3.745	3.650	3.563	3.500	29.958	36.495	42.758	48.996
Cervelo P5-Six	2.5	3.515	3.489	3.440	3.368	28.121	34.894	41.284	47.156
Cervelo P5-Six	5	3.323	3.334	3.277	3.220	26.587	33.336	39.318	45.086
Cervelo P5-Six	7.5	3.543	3.497	3.435	3.380	28.347	34.969	41.215	47.326
Cervelo P5-Six	10	3.764	3.597	3.412	3.360	30.114	35.973	40.939	47.035
Cervelo P5-Six	12.5	3.590	3.396	3.269	3.192	28.719	33.956	39.233	44.684
Reap TT	0	3.676	3.634	3.469	3.407	29.412	36.337	41.623	47.698
Reap TT	2.5	3.578	3.514	3.447	3.377	28.628	35.144	41.362	47.275
Reap TT	5	3.314	3.306	3.252	3.199	26.510	33.059	39.022	44.792
Reap TT	7.5	3.410	3.384	3.263	3.231	27.280	33.839	39.160	45.234
Reap TT	10	3.563	3.430	3.325	3.275	28.502	34.305	39.902	45.851
Reap TT	12.5	4.043	3.995	3.908	3.863	32.344	39.954	46.893	54.085
Delta	0	-0.068	-0.016	-0.095	-0.093	-0.546	-0.158	-1.135	-1.299
Delta	2.5	0.063	0.025	0.006	0.008	0.506	0.250	0.078	0.119
Delta	5	-0.010	-0.028	-0.025	-0.021	-0.077	-0.277	-0.296	-0.294
Delta	7.5	-0.133	-0.113	-0.171	-0.149	-1.067	-1.129	-2.055	-2.092
Delta	10	-0.202	-0.167	-0.086	-0.085	-1.612	-1.668	-1.037	-1.184
Delta	12.5	0.453	0.600	0.638	0.672	3.626	5.998	7.660	9.401

Figure 33 - Wind Tunnel, Cervélo & Reap

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