AERODYNAMICS OF HIGH PERFORMANCE RACE BICYCLE WHEELS

In cycling, particularly time trialling and triathlon competitions, the equipment choice plays a huge role in the overall performance, as the rider has to fight against the clock without outside assistance. As the power, needed to overcome aerodynamic drag, increases cubically with speed, good aerodynamics are essential to competitiveness in these kinds of races. The wheels are only one part of the overall aerodynamics of the unit rider-bike (~10%), however an athlete can gain significant time advantages with the optimum choice of wheels and tyres. With competitions often being decided by a handful of seconds after several hours of racing, this can be the difference between winning and also-ran.

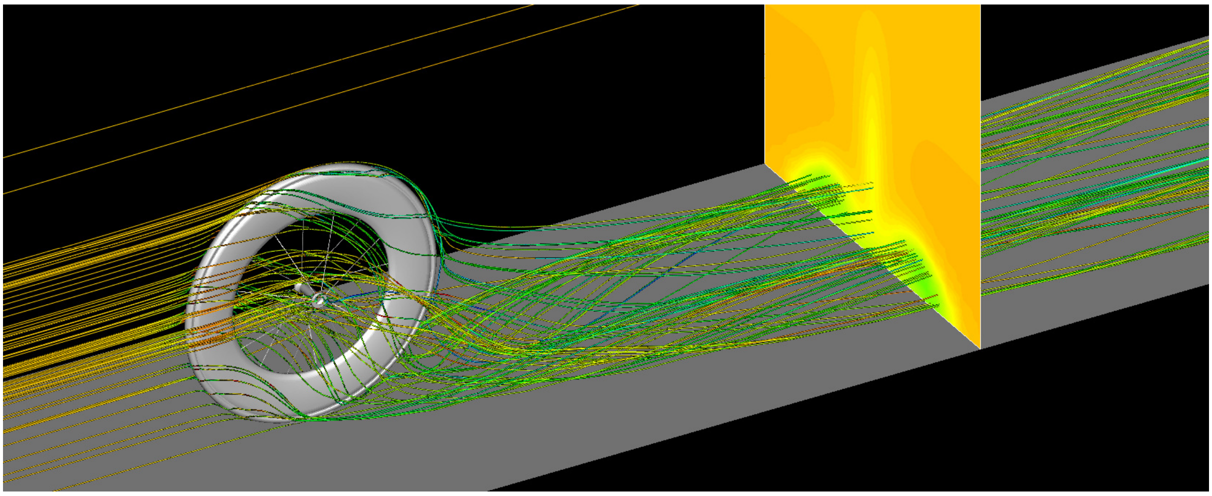

Figure 01: Streamlines around a Zipp 1080 at 40 km/h

As real world race conditions never offer perfectly still air or frontal wind (0°), bicycle wheels have to be developed for upstream flow angles, which are experienced in typical weather conditions by a typical racing cyclist, i.e. apparent wind angles between 0° and 30° yaw angle.

Within this study 6 different wheel geometries were investigated in terms of drag and side force to determine whether CFD can be applied to optimize bicycle wheels aerodynamically. They differ in rim depth, rim profile and spoke count. All investigated wheels are thought to be aerodynamic wheels with rims built of carbon and considerably deeper (44mm – 111mm and a full disc) than traditional aluminium rims.All CFD simulations were performed with AVL FIRE ® v2008.1 in steady state mode using the k-e-turbulence model. The virtual wind tunnel consists of a moving road, inlet boundary with 11.11 m/s (40 km/h) inlet velocity and 101,325 Pa outlet pressure boundary. The three remaining sides are defined as symmetry boundary.

The rotating wheel is modeled applying the MRF (Multiple Reference Frame) method. Therefore the entire wheel is covered inside the MRF volume with an arbitrary interface between MRF volume and the wind tunnel. For all simulations the wheels rotate around the y-axis with the respective rotational speed of 316.73 rpm. The yaw angle was varied by turning the wind tunnel around the z-axis through the respective angle. The models were meshed with Fame Advanced Hybrid, one of the automated grid generation tools provided with AVL FIRE ®. The overall simulation mesh consists of 1million (disc) to 6million (Zipp 303) cells.

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CFD Results

The simulations showed a large dependency of the yaw angle on the drag force, as it is already known from various wind tunnel tests published in bike journals and by wheel manufacturers. For 0° yaw angle, i.e. no wind or head/tail wind, the difference between the wheels is marginal.

The disc wheel showed decreasing drag with increasing yaw angle, up to 20° yaw, where the drag even turns negative.
As a rough rule one can say, the deeper the rim the less the aerodynamic drag. But differences in the profile can make the difference on the track. The Campagnolo Bora and the Lightweight with almost the same rim depth show big differences in drag characteristics, and the smallest rim of the Zipp 303 even shows better aerodynamic behaviour than the Campagnolo Bora wheel.
The side force, i.e. the air forces acting perpendicular onto the wheel, depends on the projected area in y-direction. That means, that the side force increases with increasing rim depth. The gradient is linear over the yaw angle, except for the disc wheel.

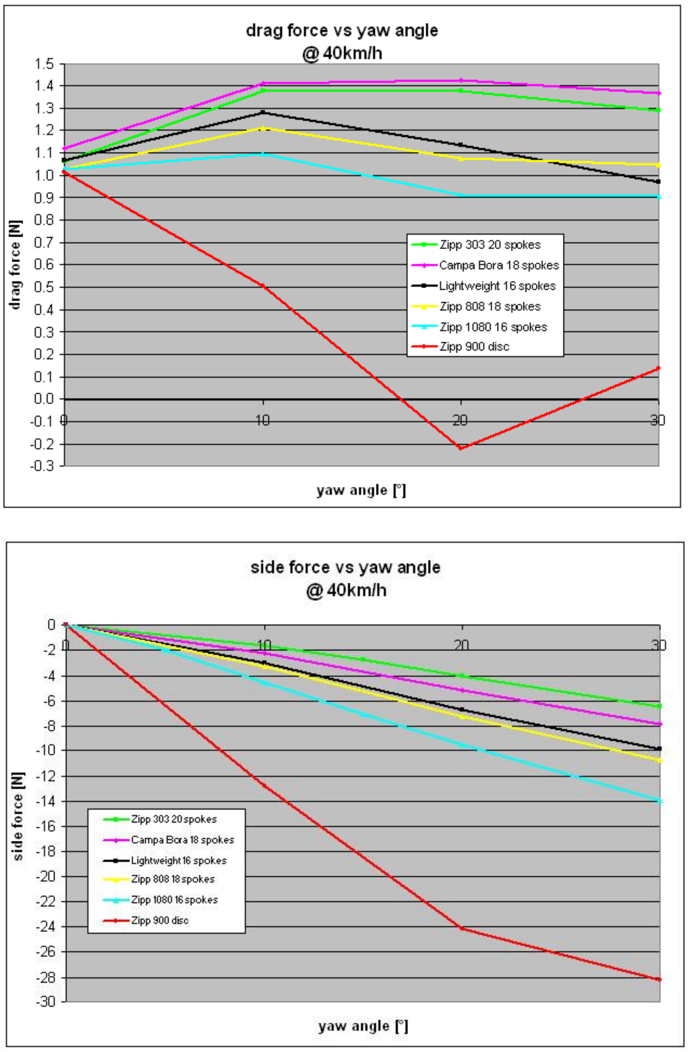

Figure 02: Drag and side forces versus yaw angle computed for different wheels

One of the big advantages of CFD simulations is the possibility to visualise the streamlines, i.e. the characteristic flow around a part. In the case of a rotating wheel the air is deflected downwards by the front part of the rim and forms big eddies close to the ground on both sides behind the wheel.

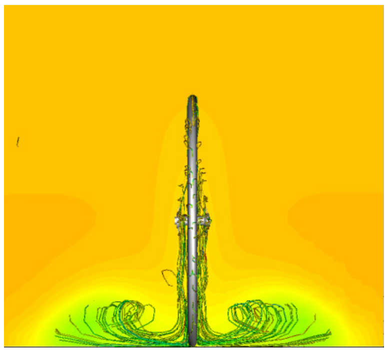

Figure 03: Velocity field behind a Zipp 1080 at 40 km/h, 0° yaw angle

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Comparison with measurements

Wind tunnel measurements of the independent German bicycle journal *Velomotion* show the power, which is needed to move a wheel through the air at 45 km/h bike speed. Among the tested wheels are the Zipp 808 (green), Lightweight (red) and a disc wheel (orange), which are also part of our study.

The disc wheel and the Lightweight show very similar characteristics in measurement and CFD simulation. Also the characteristic of the Zipp 808, to generate more drag than the Lightweight for yaw angles > 20° corresponds with the CFD results.

The manufacturer Zipp measured the side forces on different wheels as plotted in figure 5.

The result is pretty much the same as in the CFD simulations: with increasing rim depth and yaw angle the side forces increase. The gradient is linear over the yaw angle, except for the disc wheel.

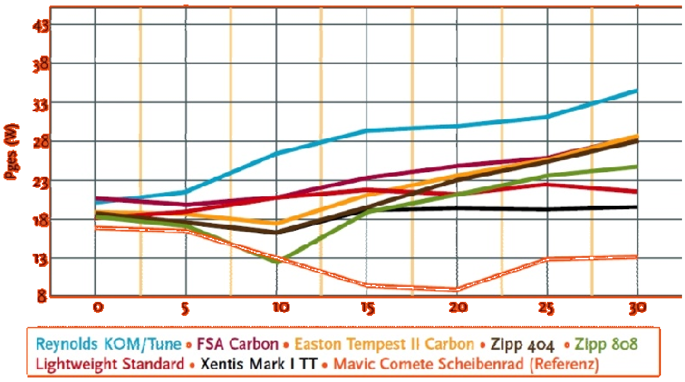

Figure 04: Wind tunnel tests [1] performed by *Velomotion* show the power needed to move the wheel at 45 km/h at different yaw angles

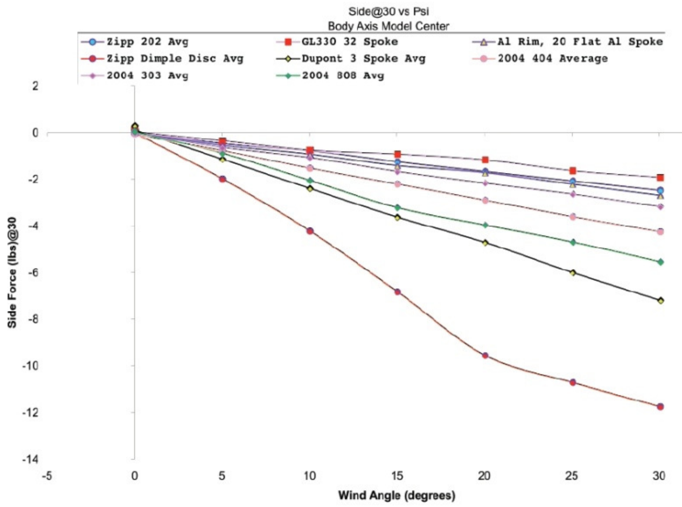

Figure 05: Wind tunnel tests [2] performed by wheel manufacturer *Zipp* show the side forces at 30 mph at different yaw angles

Time gains

It may be nice to know, that one wheel performs better than another. But when it comes to racing, it is the time differences that count.

The velocity of the bike and rider is the result of the balance between the propulsive force applied to the pedals and the sum of all the resistive forces acting on the bike. These resistive forces include some obvious (wind resistance or drag, ascending slopes and rolling resistance) and some less obvious (inertia of the wheels and efficiency of the drivetrain) forms of resistance. Martin et al. (1998) proposed an equation to model the power required to maintain any velocity:

$$P_{Total} = P_D + P_R + P_F + P_S$$

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with

P_{Total}	-	total power required to maintain a certain velocity
P_D	-	power to overcome drag
P_R	-	power to overcome rolling resistance
P_F	-	power to overcome friction
P_S	-	power to climb a slope (negative when descending)

With this equation it is easily possible to calculate the average velocity for different bike & rider combinations on a given course.

	professional rider		amateur rider		hobby triathlet	
avg. Power	450 W		350 W		250 W	
front wheel	Campa Bora	Zipp 1080	Campa Bora	Zipp 1080	Campa Bora	Zipp 1080
rear wheel	Campa Bora	Zipp Disc	Campa Bora	Zipp Disc	Campa Bora	Zipp Disc
v avg. [km/h]	47.97	49.27	43.93	45.11	37.43	38.30
time for 40 km	50min 1.76s	48min 42.63s	54min 37.5s	53min 11.51s	64min 6.9s	62min 39s
time gain [s]		**79**		**86**		**88**

Table 01: Time gains on a 40 km course due to the use of wheels with better aerodynamics

On a flat 40 km time trial a professional rider can gain 79sec with the fastest wheel set (Zipp 1080 & Disc) compared to a Campagnolo Bora wheel set.
The slower the rider, the larger the time gain with a faster wheel set, as the aerodynamic advantage of the wheels remains the same, but the slower rider spends more time on the course and thus can save more time with faster wheels.

Conclusions
The results of the CFD simulations, and the subsequent comparisons with the wind tunnel test results, proves that AVL FIRE ® is a valid tool to investigate the aerodynamic behaviour of bicycle wheels. It is not only possible to determine aerodynamic drag values, but one can also visualise the airflow around the wheel and detect areas of flow separation, resulting in increased drag. Together with the simulation method developed and applied by WING-LIGHT.de AVL FIRE ® is an excellent, time and money saving tool to help to design improved wheel geometries.

WING-LIGHT.de is a small engineering enterprise that provides CFD services to cycle and cycle component manufacturers but also advises cyclists in selecting their equipment.
The authors of the article are both amateur cyclists participating in numerous national and international competitions. Including their trainings they ride about 12000 km per year.

Sources:

[1] Bicycle journal Velomotion #1-2/2007: comparison of 7 different carbon bicycle wheels, windtunnel measurements
[2] www.zipp.com: Zipp windtunnel measurements,

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