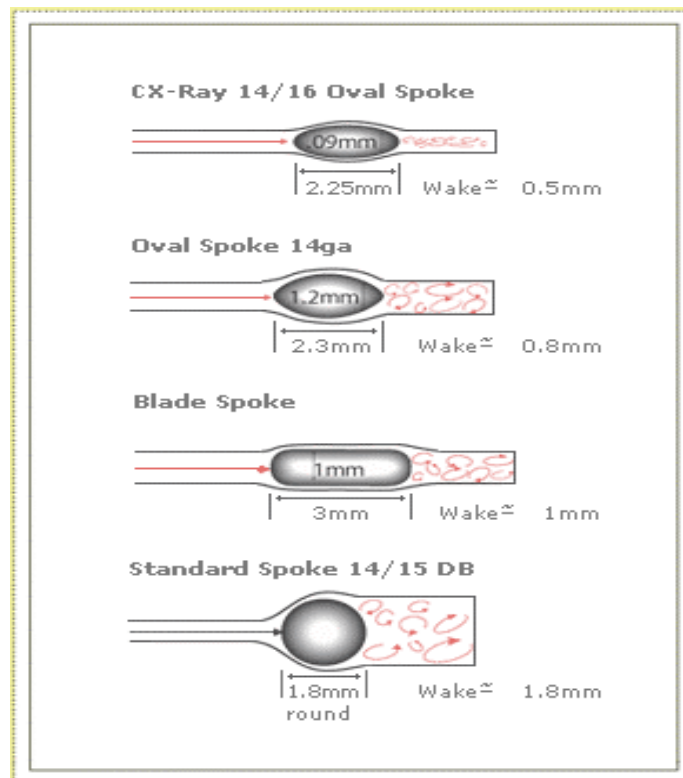


## A Note on Spoke Shape in Modern Aerodynamic Bicycle Wheels

### Spoke shape

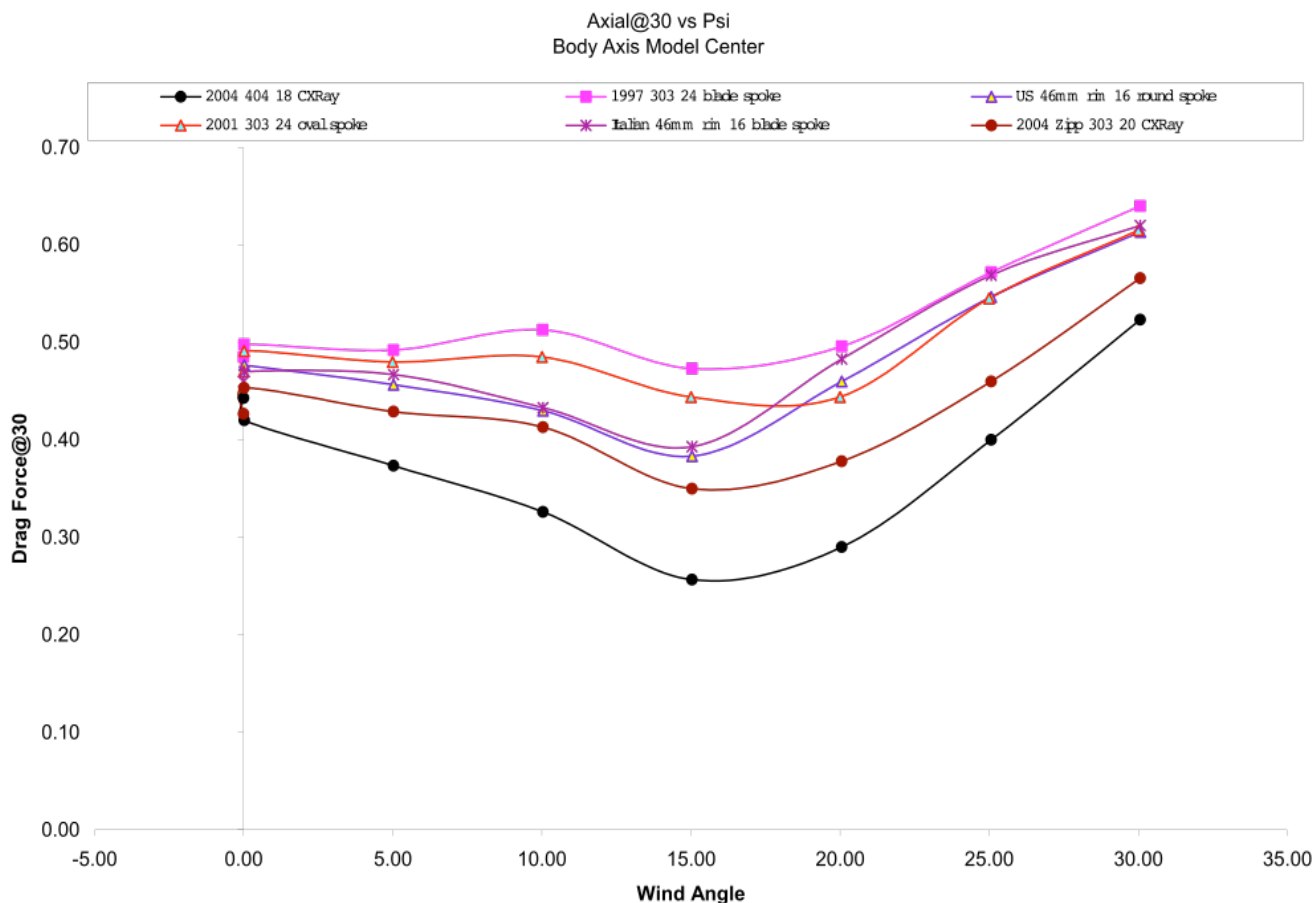
One of the key drivers of the decreased spoke count movement was that early testing showed large drag decreases with decreased spoke count. Round is a very non-ideal shape for anything which must be propelled through the wind, and the early testing was all conducted using varying counts of round spokes, thus reducing the spoke number could have led to large drag reductions in a wheel. This is one of the reasons that rim shape is so critical to blending and smoothing the air coming off of a tire, the tire is essentially round and the only way to improve its performance significantly is to control the downstream airflow in such a way as to reduce pressure drag. With spokes, however, we do not have the luxury of being able to build structure onto the trailing edge as we do with a rim. Spokes are generally designed primarily for structural properties including fatigue and ultimate strength followed by weight, with aerodynamics being more of an afterthought coming about in the late 1980's and early 1990's. The first aerodynamic spokes were bladed; essentially, a round spoke was smashed in the center to form a thin rectangular cross section. This was an improvement, but hubs now had to be slotted to accept these special spokes, and they tended to be heavy as only straight gauge spokes were generally bladed. The next improvement came in the form of ovalized spokes. These had the advantage of not requiring slotted hubs, but were generally still made from straight gauge wire, and were still heavy. The beauty of the oval profile is that it is very aerodynamic over a wide range of wind angles and conditions. Bladed spokes are more aerodynamic than round spokes at most every possible condition, however, they do add some side force to the wheel in a cross wind, whereas oval spokes tended to yield an aerodynamic improvement and reduced side force. Zipp switched over to ovalized spokes in 1998 after testing showed them to be a more beneficial design overall yielding both improved aerodynamics and improved handling.

In 2002, Zipp made the move to a radically new spoke from a small Belgian company. This spoke had taken the pro peloton by storm, and in a visit to Europe in 2001, Zipp engineers saw mechanics from some 7 teams actually rebuilding their sponsored wheels with these exotic and expensive new spokes. The spoke was the CX-Ray, a double butted spoke, ovalized through coining, and post heat treated. The test results showed a more than doubling of fatigue life, and a slight improvement in aerodynamics over the existing 14 gauge ovalized spoke. The aerodynamic benefit came with a weight benefit as well since these spokes were ovalized on a 16 gauge butted section, so Sapim had produced an aero spoke with the weight of a superlight butted spoke.



## Pressure wake formation for various spoke shapes

The chart above shows the various spoke shapes and sizes, with their computer predicted pressure wakes at 30mph. The computer simulations predict numbers which do correlate with real world testing of built wheels. Note with the round spoke, that the wake will generally be equal to the diameter of the spoke, such that even the thinnest butted spokes have pressure wakes larger than heavier gauge bladed or ovalized spokes. Some have theorized that bladed or ovalized spokes will 'stall' at higher wind angles causing increased pressure drag, but wind tunnel testing has thus far shown this to not necessarily be true in any of the wind angles generally assumed to normal. Two different 303 wheels were used, both with the 2001 'V' shape which has since been changed, however, the only difference between them is spoke shape. Also shown are two competing carbon wheel models, one from an American company, another Italian. These rims are nearly identical in shape, with one using round and the other bladed spokes. The two lower lines represent current model 303 and 404 wheelsets integrating both CX-Ray spokes, and the latest rim shapes optimized over the past 4 years.

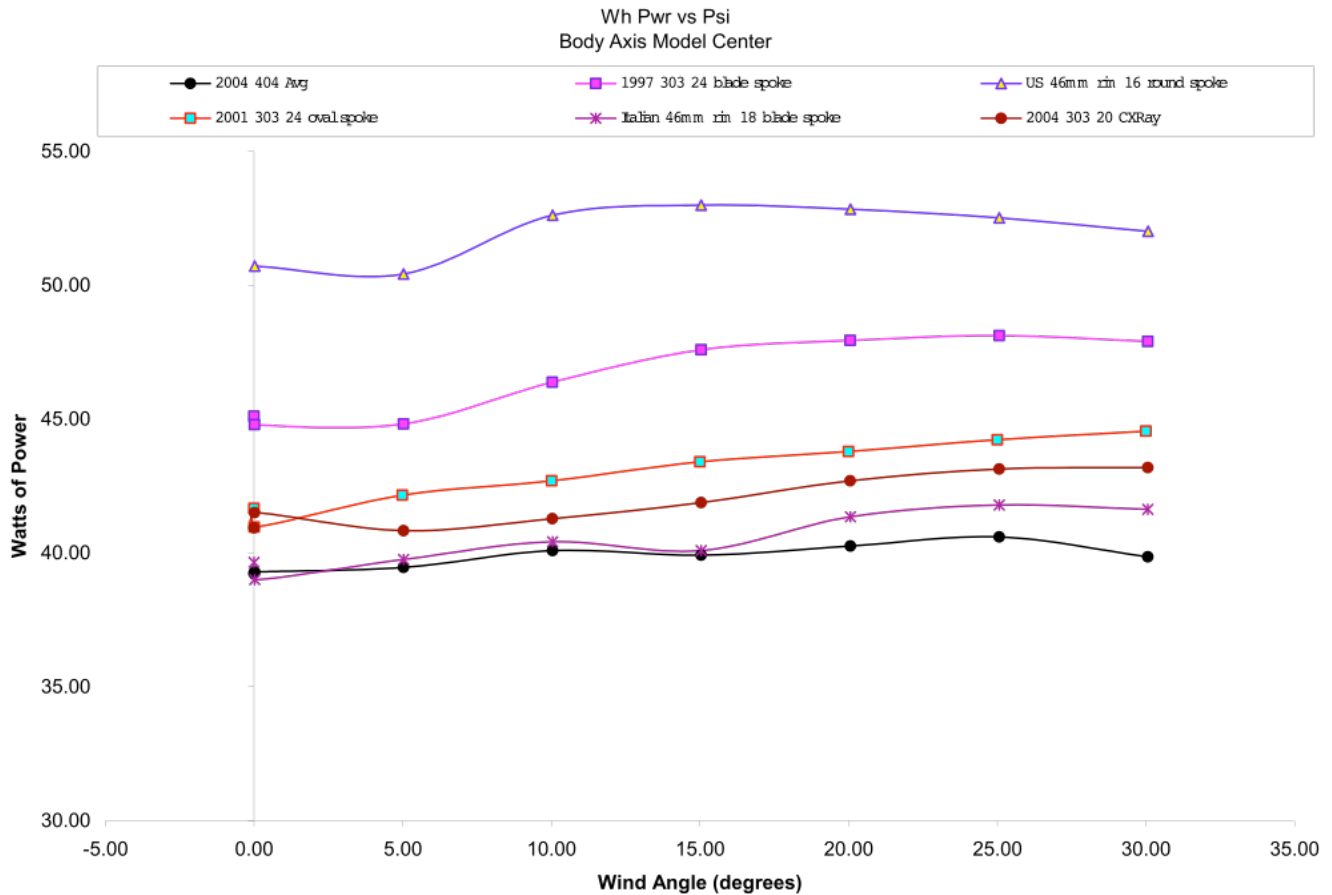


At first glance, one notices the improvement from bladed to oval spokes in the older 'V' shaped 303 wheels. Also of note is that the wheels of that time period used 24 spokes instead of the current 18. Amazingly, the difference between the 2001 303 with 24 spokes and 'V' shaped rim is huge when compared to the latest generations 303 rim shape utilizing Zipp's patented bulged rim shape and only 20 CX Ray spokes. It should also be noted that there were 4 major revisions to rim shape and spoke type between 2001 and present leading up to this major improvement. These changes require major tooling and redesign changes within the company, requiring great cost both monetarily and in time, but the overall results are clearly worth the effort.

The second thing one might notice is that the wheel with 16 round spokes has slightly lower drag than the one with 18 bladed spokes, which is confusing because the article just stated that blades were more aerodynamic. But now for the rest of the story. First, the distance between the two curves is within the margin of error of the wind tunnel balance and despite the tests representing averages, these two tests each only have three sets of data to average from, plus the rims are slightly different shapes despite being identical in depth and width. Secondly, the

aerodynamic forces on the wheel are only one component of the drag of the wheel itself. The wheel in the wind tunnel is being spun at a constant 30mph during testing, and by measuring the wattage required to spin the wheel during the testing we can determine effectiveness of some of these small changes.

Below is the graph of the identical test shown above, however the data represented is not from drag, but wattage required to spin the wheel during this drag test. What you will notice is that while round or bladed spokes, or spoke count may not drastically affect the aerodynamic loads on the entire wheel, the power necessary to spin that wheel can vary dramatically.



Perhaps the most noticeable feature of this graph is the very high wattage of the round spoked 46mm deep wheel. Requiring more than 10 additional watts to spin when compared to the almost identical bladed spoke 46mm deep wheel, with which it shared nearly the identical drag curve! Also, of note is the improvement in performance of the historical 303's, with the oval spokes proving to be slightly better than the bladed spokes when combined with the same rim. Also of note is the slight aerodynamic power improvement between the 2004 model 303 with 20 CX Rays vs. the 2001 303 with 24 bladed spokes. Individually, the graphs show slight improvements between models, but taken together, the overall wheel performance is quite large. The 46mm Italian wheel has requires lower wattage to spin than the 303 because it has shorter spokes (deeper rim). The portion of the spoke closest to the rim is the portion moving the fastest through the air, and the portion generating the most drag, this is why generally deeper rims will have generally lower drag and require less wattage to spin, assuming that other best practices are utilized in the design of the wheel.

### Conclusion

Even the best rim designs and intentions can be negated by poor spoke choice. Round spokes offer very good strength and fatigue performance, but hold a substantial aerodynamic performance penalty and should be avoided in high performance aerodynamic wheels. The aerodynamic power differential between round and oval spokes is sufficiently higher than any possible weight savings, equating to tens of pounds of additional weight to the bike, so round spokes should be avoided regardless of weight advantage. Fortunately, ovalized spoke technology and heat

treatment technologies have allowed the CX-Ray to be as light as the lightest round spokes, while also being superior aerodynamically. Many wheel companies avoid the CX-Ray due to its extremely high price (roughly 4 times the cost of butted round spokes) but when ultimate performance is desired, there is no other logical option.