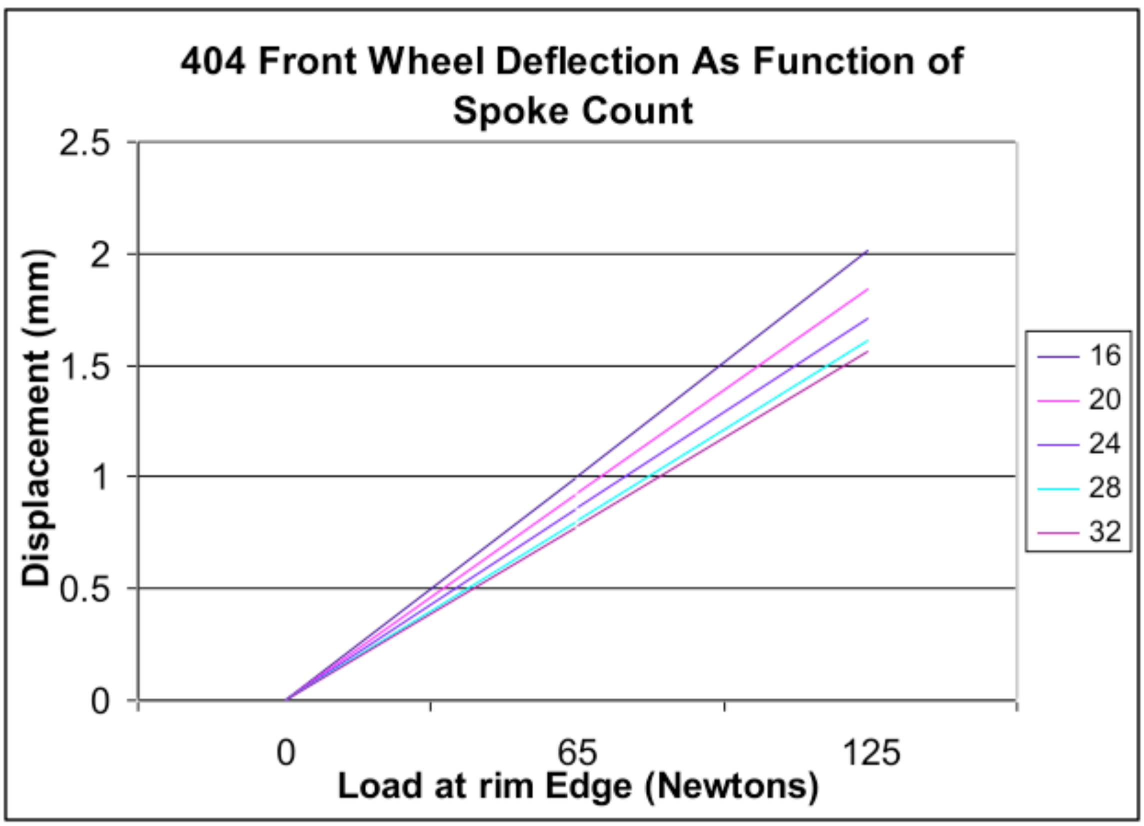
A note on Spoke Count in Aerodynamic Bicycle Wheels

Since the advent of the modern deep section aerodynamic bicycle rim, there have been numerous and often divergent theories about what constitutes an aerodynamic spoke configuration. Theories even arose in the mid 1980's thinking that higher spoke count wheels would force the air to move around the entire spoked area of the wheel, causing the wheel to behave similar to a disc. This particular theory was quickly thrown out as field studies showed riders on 48 spoke wheels working hard to keep up with those on 28 spoke wheels, but many disagreements and discrepancies still remain. By the late 1990's, the big debate seemed to relate to how few spokes one could feasibly use, and whether the spokes were best shaped round, oval, or flattened. Another raging debate was occurring between rim and wheel manufacturers as to whether hidden or exposed spoke nipples were more aerodynamic, as well as possibly stronger. The information represented below is the culmination of physical study on bicycle rims and wheels undertaken over the last 4 years specifically, and the wind tunnel information relates to a 50 hour session occurring in January 2004 at Texas A&M University LSWT, during which these issues and others were specifically tested.

Spoke Count
The easiest way to measure the benefits of increased or decreased spoke count is to simply build prototypes and test them for certain feasibility criteria. The primary issues to most racing athletes are: wheel stiffness and ride qualities, wheel aerodynamics, and wheel strength/durability. Clearly the durability issue is paramount as a wheel which fails during an event negates any other possible positive features which it may possess. The stiffness and aerodynamic issues are slightly more difficult to address. Wind tunnel data, and wheel stiffness testing show that both of these features are dependent on spoke count, but in an inverse manner. The simple graph below shows the stiffness of 4 identical 404 front wheels built with only spoke count changing



Wheel deflection with various spoke counts (lower is stiffer)

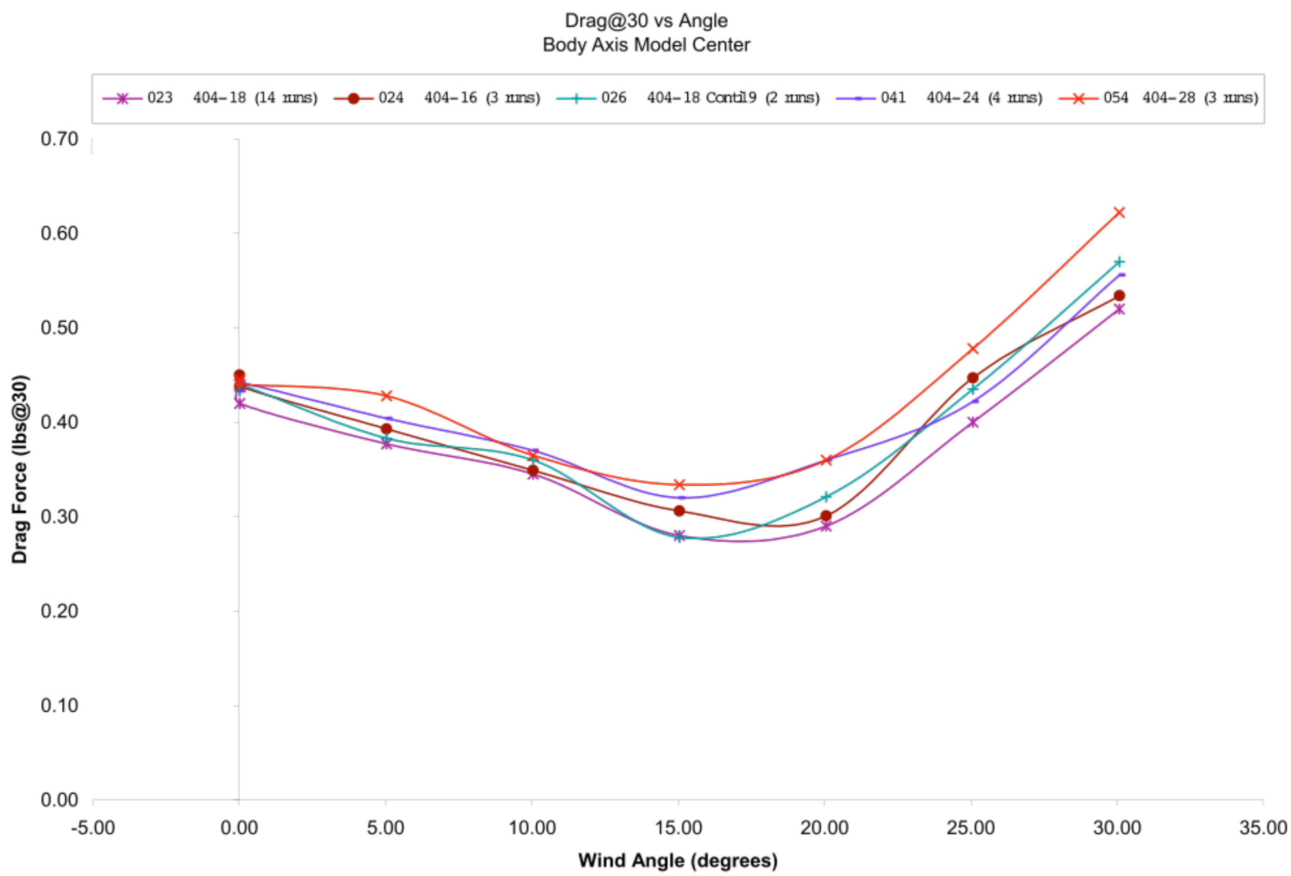
One interesting note is that the wheels become stiffer with higher spoke counts, but in a decreasing order of magnitude. You will notice that the 4 additional spokes from 16-20 spokes increase stiffness by 9.2% while the 4 additional spokes from 20 to 24 increase stiffness by only 7.5% and the 4 additional spokes between 28 and 32 yields only a 3.2% increase in stiffness. (This is largely due to the relative ratios of spoke counts and design of the study where spoke count increases were all performed by adding the same number of spokes (4). Proportionally 20 spokes is 125% more than 16, but 32 spokes is 114% more than 28 and hence the decreasing ratio, but also of note is that 25% more spokes yields only 9.2% more stiffness).

What this graph and others will not show, is how this wheel feels to the rider. One goal in optimizing spoke count is to determine what 'feels good' to athletes of various weights, or various riding styles, and optimize the product to those goals. In this instance, a 404 front wheel in production is built with 18 spokes, because that gives the largest range of acceptability among rider weights and events. Zipp generally tells customers that standard spoke counts are good for triathletes up to 225 lbs and road riders up to 200, the differing weights for the same wheels reflect the different needs of road riders and triathletes. A road wheel is expected to sprint well and corner with a certain feel, whereas a triathlon wheel needs to handle with confidence and comfort while being as aerodynamic as possible. Heavier riders are recommended to move up to the Clydesdale wheels which utilize higher spoke counts for greater stiffness. The standard 404 rim has identical construction and durability to a Clydesdale rim, so the only differentiator is in spoke count, and therefore stiffness. At the other end of the coin, very light riders may special order 16 spoke wheels if they wish to save the 9 grams in spoke weight and are not as concerned with wheel stiffness. For a rider only weighing 125lbs, the loss of 9% stiffness is of little issue, particularly on a wheel which a 200 lb rider will generally find acceptably stiff. However, further recuding the spoke count generally does not make sense as the risk of spoke failures begins to increase dramatically as explained below.

Rear wheels utilize more spokes as they encounter higher lateral forces due to rider weight distribution, must deal with torsional loading due to tractive forces (drive forces from the chainset), and simultaneously have decreased flange spacing due to geometric conditions (drive side flange competes for real-estate with the drivetrain). Generally, Zipp wheels shoot for identical front and rear wheel stiffnesses, but the advent of 10 speed systems has made this increasingly difficult. For 2005, the rear hub geometry has changed substantially and now utilizes a larger drive side flange spaced closer into the cassette in order to build stiffer rear wheels. One effect of this is that the 303 wheels have moved from 28 to 24 spokes with no sacrifice in stiffness. 404 wheels on the other hand remain at 24 spoke rear as 20 spokes resulted in a slight decrease in stiffness when compared to the previous year, and the straight pull hub geometry makes a 22 spoke rear hub impossible, this means that the 404 rear wheel increases in stiffness of roughly 6.5% while decreasing slightly in weight due to the new, lighter hub.

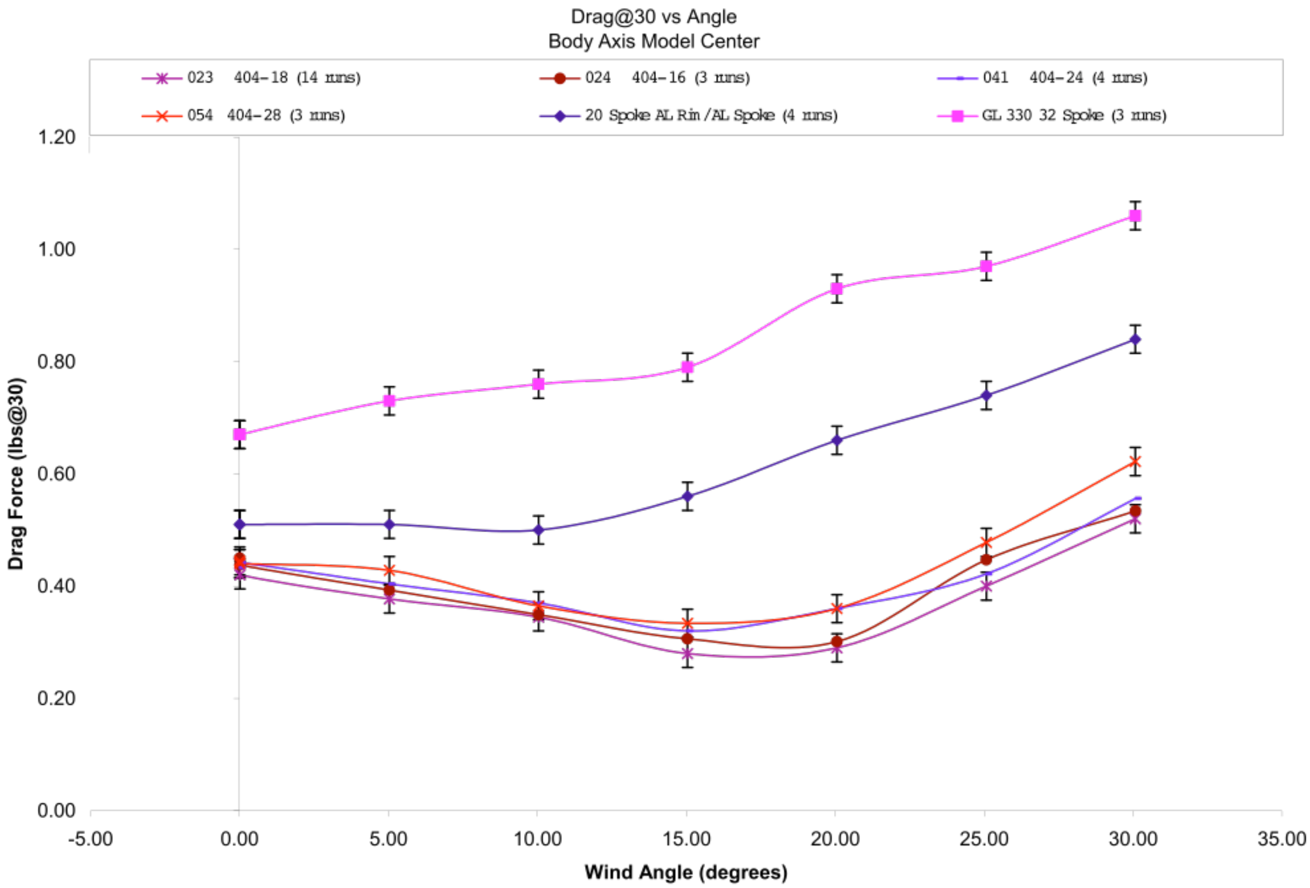
Other than reducing weight, the other often touted reason for reducing spoke count is for aerodynamics. Special spoke counts are often requested for special events, and just as we will not argue that decreased spoke count does have some positive aerodynamic benefits, we will argue that these benefits are of ever decreasing proportion, and may have other consequences. For this reason, Zipp refuses to build wheels utilizing fewer than 16 spokes. We feel that this is the best blend of aerodynamics and acceptable stiffness, while also allowing for long spoke life without fear of premature spoke fatigue and failure. One other important feature is that a 16 spokes seem to be about the lowest number possible which will still leave a ridable wheel in the event of a spoke failure. This is a point which cannot be overemphasized, if you are unable to finish your event due to a spoke failure, then that product offers no advantage. This is true regardless of whether the spoke failed due to stress, fatigue, or due a tangle with another rider's rear derailleur or pedal, if you cannot ride it, none of the other features matter.

The graph below shows the differences in aerodynamics between the spoke counts ranging from 16-28, and may be surprising in its lack of major performance differences. In fact, the 4 spoke differences between wheels are largely within the margin of error of the wind tunnel itself. It should be noted that each line on this graph represents a minimum of 2 runs averaged together in order to minimize margin of error.



At first glance many will look at this and determine that the lower spoke count wheels have a distinct advantage, although the 18 spoke wheel has the lowest total drag of all. One reason for this may be due to its average of 14 separate runs as opposed to only 2-4 runs for the other wheels. Since these particular runs were all taken over a 3 day period, there could be other factors as well, such as temperature and humidity effects. Because of this, we accept the margin of uncertainty to be 0.5 pounds per data point. This means that almost all of these wheels have overlapping uncertainties at almost every data point. Without hundreds of additional runs conducted in extremely controlled test conditions, it is difficult to say that there is a distinct advantage to one spoke count or the other. In fact, much of what one may read into this graph is a result of the scaling of the drag on Y axis. Also, we have thrown in an 18 spoke 404 with 19mm Continental track tire to show the differences a tire can make. I this instance, the wheel appears to possibly be slightly slower than the 404 with 21mm Corsa CX tire and 18 spokes, but considering margin of error, we would have to say that the two curves are essentially the same, with the 19mm tire curve tending to have higher drag.

To highlight this scaling issue, we will look at the identical graph with the inclusion of a very popular aluminum wheel, and a classic standard wheel from 10 years ago. The popular current wheel is a machined aluminum rim with bladed aluminum spokes, with machined reliefs between spoke nodes. The classic standard wheel is a GL330 tubular rim from 1996 utilizing 32 round 14/15 spokes and a Record hub. Both wheels were tested with the identical Corsa CX tire as the other Zipp wheels. The higher drag skews the scale somewhat and makes the differences in the various 404's seem even smaller, particularly in light of the massive drag reductions of the deep section wheels compared to the standard aluminum rims.

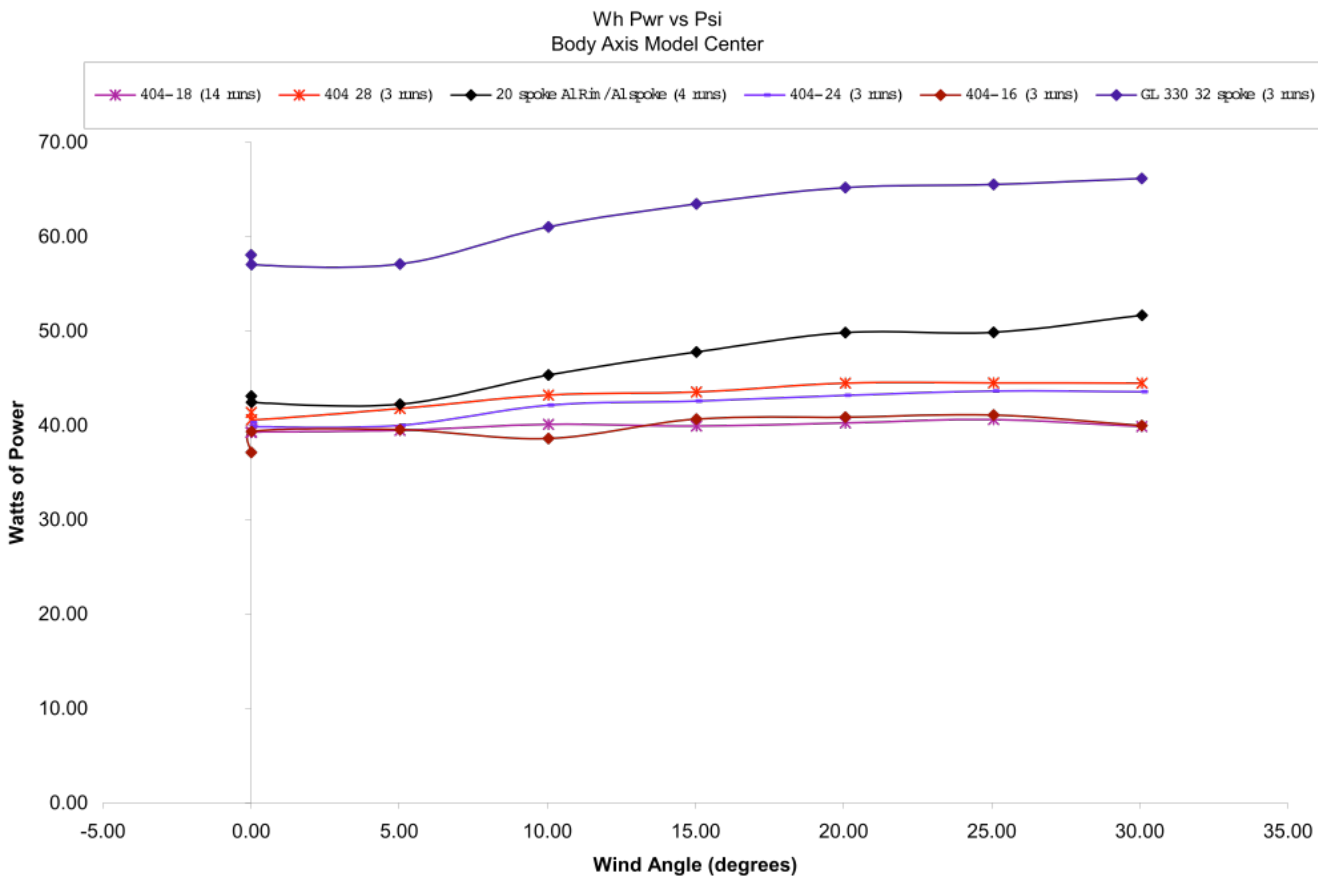


Error bars have been included on this graph to show how many of the uncertainties in the deep section wheels overlap each other, but the margins between the deep section wheels of any spoke count and the two traditional type wheels are vastly separated. The differences in the two aluminum wheels show essentially the difference between spoke count and shape for two relatively standard rims of similar geometry. The reduction of 12 spokes, combined with the bladed spoke shape compared to round makes a considerable difference between the two, but the overall scale of the graph really makes you appreciate the advantages of modern carbon wheel technologies.

Wattage to Spin

The drag graphs bring us to the next major point with aerodynamic wheels, wattage required to spin the wheel in the airflow. The drag of the wheel is only one component of the spinning wheel system, with the other being the wattage (power) required to spin that wheel during the test. Simultaneous to all of this wheel testing, the wattage requirements are being measured and recorded in a second set of graphs, and the information hidden within can be quite revealing, or quite perplexing depending on the situation. Much of the information on wattage to spin is also contained in **A Note on Spoke Shape Utilized in Aerodynamic Bicycle Wheels**, but we will drop the graph in below to help highlight the spoke count issue as well. Since our testing on spoke count contains data solely pertaining to change in spoke count of a wheel with all other factors remaining constant, the graph below becomes quite interesting and a bit perplexing at the same time.

Of note is that the 18 spoke wheel seems to require fewer watts to spin than the 16 spoke wheel, and the 28 spoke wheel requires only 4 more watts to spin at its worst data point. The answers here are similar to those found in the aerodynamic graphs on this topic in that they relate to margin of uncertainty. The wattage test has a higher uncertainty than that associated with the wind tunnel balance, in fact, the uncertainty is roughly 4 watts, so in order to make really valid conclusions we should really have a minimum of 7 runs averaged for each spoke count before we could even begin to compare the data statistically. The reality is that the wheels seem very similar in performance because they are, and whatever differences exist are quite small (less than +/-2 watts). The more traditional wheels on the other hand, so show some large differences between them, with the 20 bladed spokes being more than 10 watts more efficient than the 32 round spokes. This difference is easily large enough that conclusions can be drawn despite the margin of uncertainty of the test itself.



Conclusion

In conclusion it seems that the basic conceptual design of the wheel, and it's spokes, is more important than small detail changes in spoke count. Individually, these changes are moderate, but taken as a whole, the results are quite large. One could theorize that changing from 32 round to 32 oval spokes would provide a differential in wattage to spin, by as much as 10 watts, but to move from 32 round spokes to 18 or 20 ovalized ones can yield more than 20 watts of improvement. However, once these major improvements have been made, small changes in spoke shape or count are marginal at best. In the 404 test, we see that adding 12 additional spokes leaves us a possible increase in wattage of only 1-5 watts, and the move from 18 to 16 spokes seems to have essentially no benefit whatsoever, so the key is to be aware of what other factors may be sacrificed for these minute or nonexistent advantages.

We believe that every athlete is special, and will subject their wheels to special circumstance, or special events. In some cases, these very subtle changes may yield incremental advantages which are necessary for a certain event, but generally come with some cost. Fewer spokes means decreased stiffness and spoke life, while additional spoke counts can lead to higher power requirements, or overly stiff wheels which are punishing on rough roads. Each individual wheelset we build is designed and tailored to fit the specific design intent for which it was engineered, and for a range of rider weights and styles. Even though our standard products will be ideal for more than 95% of athletes and conditions we still do not subscribe to the system popular with some companies where you can have whatever hole count you want as long as it's 16/20 regardless of rim type or depth. Each wheel system has hub, rim and spoke count tailored to achieve certain stiffness and aerodynamic goals, but if your situation or needs differ, these features can be tailored to fit. If you feel your circumstances differ from the norm, please feel free to contact the customer service department at Zipp to inquire about our custom wheel program in which custom spoke counts and configurations can be built at your request.