Effects of

Lateral Chain Misalignment (Cross-Chaining) on Drivetrain Efficiency

&

Effects of Chainring Size on Drivetrain Efficiency

April 17, 2015

Background

It has been hypothesized that lateral chain misalignment (also known as 'cross-chaining') causes significant frictional losses in the drivetrain, and these frictional losses increase as the angle of misalignment increases.

It has also been hypothesized that a larger chainring is more efficient than a smaller chainring, given the same final effective gear ratio.

When riding in the front big ring with larger rear cogs, at what point, as the chain climbs up the rear cassette (shifting to larger-toothed cogs), does the potential frictional advantage associated with using the big ring become a disadvantage due to the increasing angular misalignment (aka heavy cross-chaining while in the big ring)?

In a derailleur-style drivetrain, the overall frictional losses can be affected by both lateral misalignment and ring selection concurrently. As multiple similar final gear ratios can be achieved by using either the big ring or small ring, it has been hypothesized that some gear ratios are less efficient based on the ring being used, whether big or small. It has also been hypothesized that an 'optimal' shift sequence exists by using only the most efficient ring/cog combinations, while still providing for a full range of final gear ratios.

This test analyzes the frictional losses of the 22 ring-cog combinations of a 2 x 11 speed drivetrain, as well as the effects of frictional losses based solely on chainring size.

Results Summary

1) Lateral chain misalignment creates frictional losses, and the losses increase as the angle of misalignment increases.

2) A larger front chainring creates less frictional losses than a smaller chainring, given the same effective gear ratio, power output, and cadence, when tested with the chain in a pure coplanar manner (no chain misalignment introduced).

3) The data shows that optimal big ring-to-small ring and small ring-to-big ring shift points exist. **When the chain is in the big ring, the frictional losses created by the lateral misalignment become greater than the big ring savings at the 9th cog of an 11sp cassette** (with the small cog being the 1st cog). In practice, when riding in the big ring and shifting the rear derailleur to larger cogs, it's advisable to avoid the use of the 9th, 10th, and 11th cogs. Beyond the 8th cog, it is more efficient to shift the front derailleur down to the small ring in conjunction with a shift of the rear derailleur to a cog that maintains a similar final gear ratio.

Test Overview:

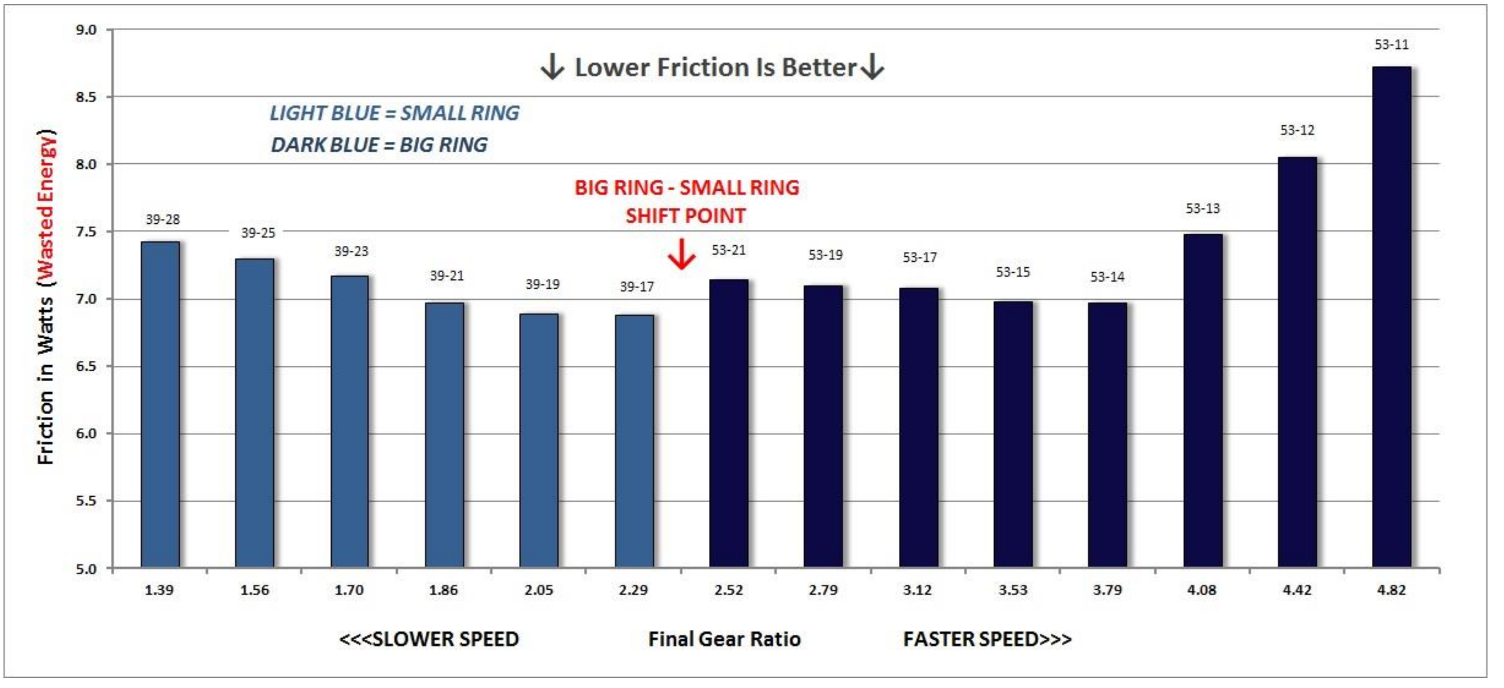
The test was performed with an 11sp Shimano CS-9000 11-28T cassette, Shimano FC-9000 53T big ring, and FC-9000 39T small ring, 95RPM cadence, and 250W rider output. Two 11sp chains were used for all test points; a Shimano Dura-Ace 11sp CN9000 and a SRAM 11sp PC Red 22. The data points in the following graphs represent the average of both chains' measurements.

For the first part of the test, the big and small chainrings were tested with each of the 11 rear cogs with the associated amount of lateral misalignment applied. The lateral misalignment occurring for each ring-cog combination was measured on an 11sp bicycle drivetrain. This identical misalignment angle was then reproduced on the test equipment. Note: two of the 22 ring-cog combinations do not exhibit lateral misalignment. Alignment of the front ring and rear cog occurs in the 53-14 (big ring aligned with the 4^{th} cog) and the 39-17 (small ring aligned with the 6^{th} cog) combinations.

A Cervelo R3 was used to obtain the lateral misalignment measurements. It is acknowledged that slight variations in lateral positioning (outboard distance from bike centerline) of the rings and cogs can occur across different manufacturers of frames, BB standards, and wheels. The effect of different positions of the natural alignment of the ring-cog is discussed later in this report.

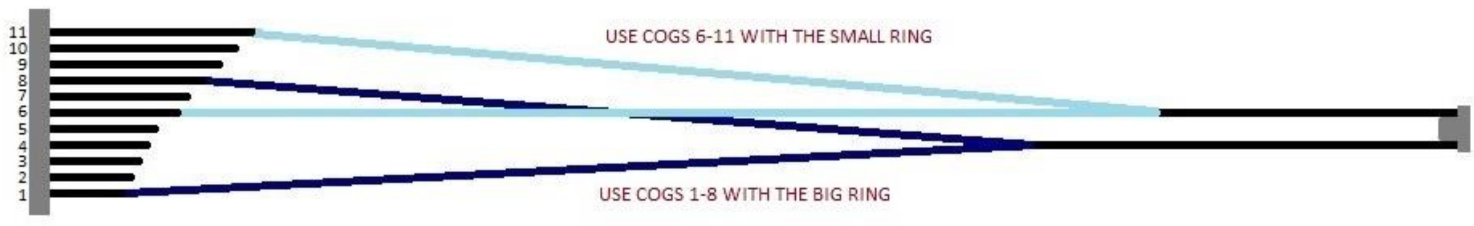
For the second part of the test, the big and small chainrings were tested with each of the 11 cogs in a coplanar manner (purely aligned with no lateral misalignment), with the derailleur still present, as with the first part of the test, to determine the effects of the big ring vs. small ring frictional losses. (Removal of the lateral misalignment variable allowed us to single out the effects of ring size alone)

Optimal Shift Sequence:



Graph 1 illustrates the optimal shift sequence using the ring-cog combinations with the lowest frictional losses yet maintaining an acceptable range of final gear ratios. The left axis represents frictional losses in watts consumed (wasted energy). Lower wattage consumption is better. The bottom axis represents the final gear ratios of the most efficient ring-cog combinations. With quick-readability and ease-of-use in mind, this graph displays only the 14 most efficient ring-cog combinations of the 22 total ring-cog combinations available (11 cogs x 2 rings). The 8 ring-cog combinations which are not included in this graph are the higher-friction combinations which fall between gear ratios of two lower-friction ring-cog combinations (i.e., the 8 ring-cog combinations which are relatively inefficient and should not be used). This graph also shows the shift point from the big ring to the little ring. When flat terrain transitions to uphill, bike speed decreases, and the chain is being taken up the cassette to larger cogs, the optimal shift point from **big ring to small ring** is after the 21T cog (8th cog). Conversely, as the terrain transitions from uphill to flat, speed is increasing, and the chain is being taken down the cassette to smaller cogs, the optimal shift point from the **small ring to the big ring** is after the 17T cog (6th cog).

Note, the bottom axis in the above graph is *not* linearly scaled with regard to gear ratio.



Drawing 1 is a visual illustration of the rings, cogs, and sweep of chain lines of the optimal ring-cog combinations. The dark blue lines represent the sweep of efficient cogs which should be used when in the big ring (1st thru 8th cog). The light blue lines represent the sweep of cogs which should be used when in the small ring (6th thru 11th cogs).

Graph 2 shows *all* 22 ring-cog combinations including the 8 higher-friction ring-cog combinations which were not included in Graph 1. The green line represents the shift pattern, and connects the most efficient gear combinations when increasing or decreasing speed.

To illustrate the rationale behind the shift pattern, assume a rider is at maximum speed on level ground, say in the 53-11 ring-cog combination. The grade of the road then increases, necessitating shifting. The rider, while staying in the 53T big ring, would shift the rear derailleur from the 53-11 combination (big ring, 1st cog of the cassette), into the 53-12 (2nd cog). As the grade of the road continues to increase, the rider would then shift into the 53-13 (3rd cog), then 53-14 (4th cog), then 53-15 (5th cog), then 53-17 (6th cog), then 53-19 (7th cog), and then into the 53-21 (8th cog of the cassette). At this point, to maintain the most efficient shift pattern, instead of taking the chain higher up the cassette into the 53-23 combination (shifting into the 9th cog), the rider would choose to shift from the big ring into the small ring, and subsequently shift the rear derailleur to the 39-17 combination (small ring, 6th cog of the cassette). The 53-23 and the 39-17 combinations are almost identical final gear ratios, 2.29 and 2.30 respectively. From a final gear-ratio standpoint, either of these two ring-cog combinations would work. However, as the graph shows, the 39-17 combination creates less friction than the 53-23 combination. Therefore, in order to maintain the lowest-friction ring-cog selections across the final gear ratio spread, the rider would shift from the big ring to small ring at this point. If the rider were to choose to not shift into the small ring at this point, and stay in the 53T big ring and take the chain up the cassette into the 23T (9th cog), 25T (10th cog), and 28T (11th cog) cogs, this will unnecessarily waste power, as lower-friction 39T ring-cog selections are available with similar final gear ratios.

Returning to the example, as the grade continues to increase, after shifting into the 39T small ring, the rider would stay in the small ring, and continue to shift the rear derailleur taking the chain up the cassette, from the 39-17 (6th cog), then into the 39-19 (7th cog), then 29-21 (8th cog), then 39-23 (9th cog), then 39-25 (10th cog), and finally into the 39-28 (11th cog).

Conversely, when the grade of the road decreases (uphill transitions to downhill) the shifting pattern would simply be reversed. Assuming a start point of 39-28 (small ring, 11th cog), the rider would stay in the small ring, shift the rear derailleur from the 39-28, to the 39-25 (10th cog), then 39-23 (9th cog), then 39-21 (8th cog), then 39-19 (7th cog), then finally into the 39-17 (6th cog). At this point the rider would not continue to shift the rear derailleur to the next available cog, the 15T cog (5th cog). The 53T big ring now offers a lower-friction ring-cog selection at a similar final gear ratio. As such, the rider would choose to shift from the 39T small ring into the 53T big ring, and shift the rear derailleur into the 53-21 combination (big ring, 8th cog). After shifting into the 53-21 combination, the rider would stay in the big ring and shift the rear derailleur sequentially from the 53-21 combination to the 53-11 combination as more speed is needed.

Flat to Uphill:

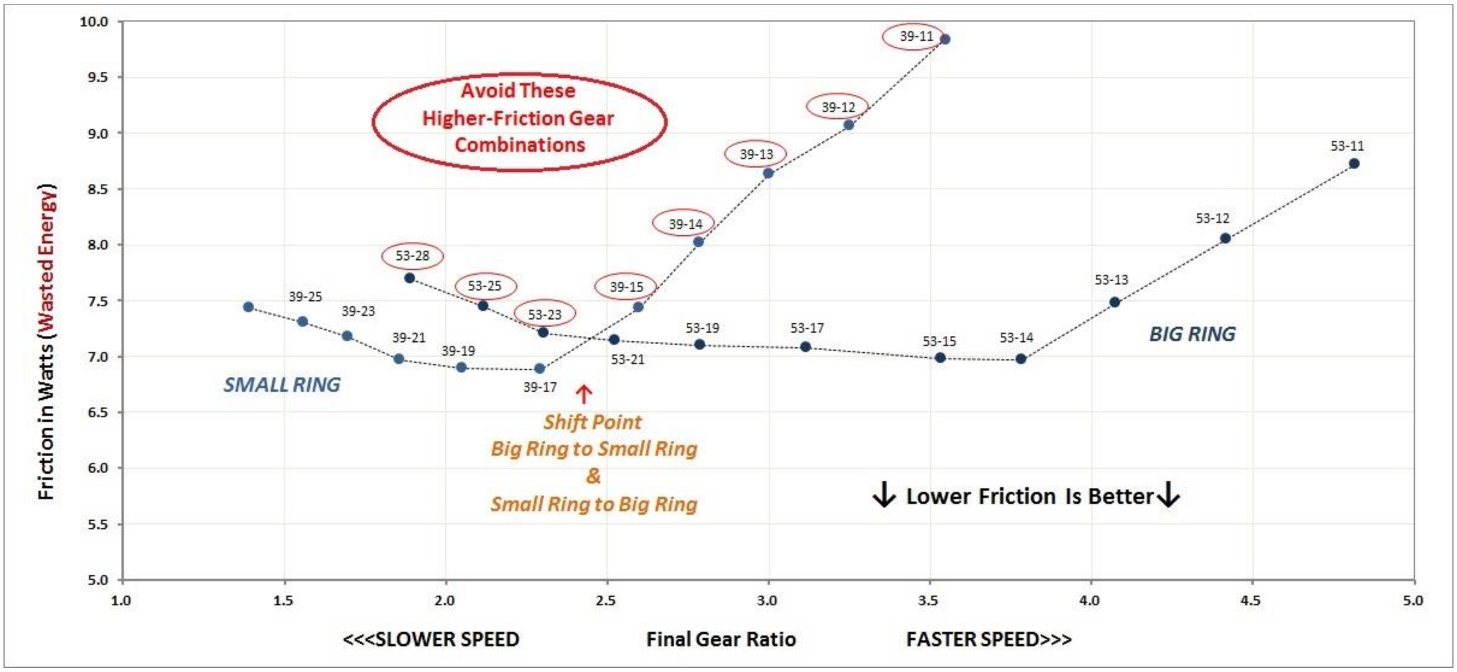
53-11, 53-12, 53-13, 53-14, 53-15, 53-17, 53-19, 53-21, 39-17, 39-19, 39-21, 39-23, 39-25, 39-28

Uphill to Flat:

39-28, 39-25, 39-23, 39-21, 39-19, 39-17, 53-21, 53-19, 53-17, 53-15, 53-14, 53-13, 53-12, 53-11.

While the data shows a savings of 0.74 watts by staying out of the big ring and biggest cog combination at lower final gear ratios (53-28 compared to 39-21; left area of the graph), the savings achieved by proper ring selection is much more pronounced at higher final gear ratios. A savings of 2.86 watts can be achieved by staying out of the small ring & smallest cog combination (39-11 compared to 53-15; right side of the graph). The important takeaway- it's not good to ride the big ring-big cog combination, but it's *much* worse to ride the small ring-small cog combination.

Diving Deeper Into The Data:



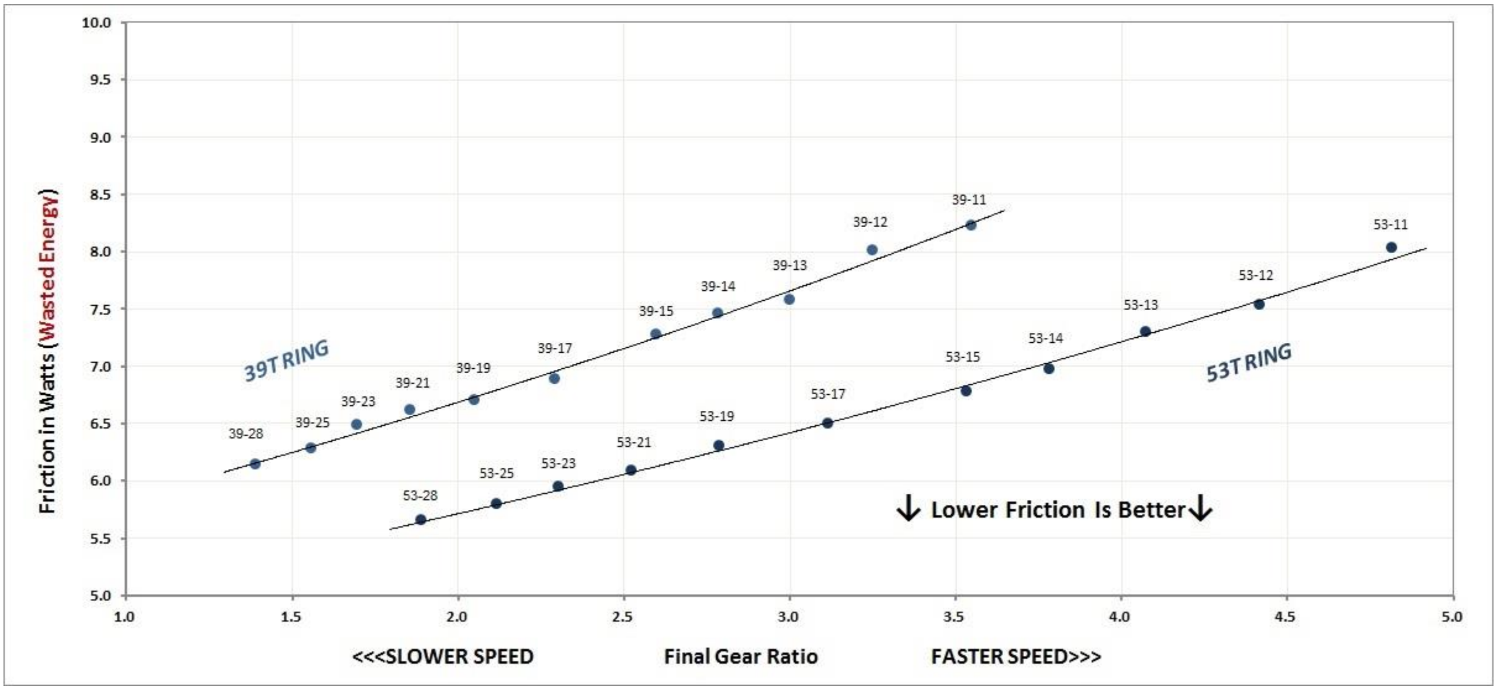
In graphs 1 and 2, the bottom axes are not to scale as the bar graph is used to provide an easy-to-read visual representation of the proper shift pattern and specific big-to-small ring and small-to-big ring shift points. Graph 3, above, shows the gear combinations on a correctly-scaled bottom axis of effective final gear ratio. The light blue data points represent the small ring with each of the 11 cogs. The dark blue data points represent the big ring with each of the 11 cogs.

The lowest-friction ring-cog combinations for each of the small ring and big ring combinations occur where the chain is aligned between the front ring and rear cog. This occurs at 39-17 (small ring, 6th cog) and 53-14 (big ring, 4th cog) respectively. On both the big ring and small ring curves, as the chain is shifted up or down the cassette, away from the aligned-chain state, an increasing amount of chain misalignment is introduced, increasing the friction levels accordingly for each cog as the chain is shifted further away from the aligned state. In this test, and for referencing later in this report, the curves seen in the above graph created by connecting the data point dots are referred to as the V-curves. The above graph shows the 39T V-Curve, and the 53T V-Curve. The bottom of the V is the point of lowest friction and also the point of rig-cog alignment for the respective ring (39-17 and 53-14).

The crossover point of the two V-curves is where the big-to-small ring and small-to-big ring shifting should occur. This occurs between the 39-17 and 53-21 ring-cog combinations.

The 8 ring-cog combinations circled in red are combinations that extend beyond the crossover point of the V-curves. These red combinations exhibit higher frictional losses than a similar gear ratio on the other curve, and should therefore be avoided. Going back to Graph 1, these ring-cog combinations circled in red are the 8 combinations removed from the graph.

Frictional Losses Due To Chainring Size (Without Chain Lateral Misalignment):



As mentioned earlier, this test contains two parts. The first part analyzed drivetrain friction with the variables of lateral chain misalignment and ring size, with the amount of misalignment based on each respective ring-cog, as is seen in a true bicycle drivetrain. In an effort to separate and analyze misalignment and ring size as unique functions, a second part of this test was performed with each ring/cog combination in a coplanar, purely aligned manner (no cross-chaining), still using the rear derailleur. By doing this, each variable can be investigated individually. Graph 4, above, shows the frictional losses of each ring-cog combination when tested in an aligned manner.

Based on the data from this portion of the test, the hypothesis is proven true that (1) larger rings are more efficient than smaller rings, given the same effective final gear ratio, power output, and cadence. And (2) within a given ring size, the frictional losses increase as the final gear ratio increases (as the rear cog gets smaller).

Why are larger rings are more efficient than smaller rings given the same effective final gear ratio? The overall decrease in frictional losses exhibited with a larger ring (and with a larger cog, as a larger cog would have be used with a larger front ring to maintain a similar effective final gear ratio) is most likely due a combination of three factors; decreased top-span chain tension, decreased articulation angle as the chain engages the front ring and disengages the rear cog, and increased articulation rate.

The general formula for chain friction (not considering lateral misalignment) is the sum of all chain engagement/disengagement points' Span Tension x Articulation Angle x Articulation Rate per unit time.

A decrease in Span Tension will contribute to a decrease in frictional losses. With a larger front ring, the top-span chain tension decreases due to a longer effective moment arm. Power output can be simplified to RPM x Torque (Torque being defined as force at a specific radius. Eg, ft-lbs). Even though the RPM and Torque are identical in both larger and smaller rings at the same rider output and cadence, since the radius of a larger ring is greater, the force (chain tension) must be lower to equal the same final torque per the equation Torque = Force x Radius. Conversely, a smaller ring has a smaller effective radius, and therefore the force (chain tension) at this smaller radius must be higher to create the same torque at a constant RPM.

A decrease in the Articulation Angle (the amount of each link's rotation as the chain engages the ring and disengages the cog) will contribute to a decrease in frictional losses. As the front ring and rear cog both increase in size (while maintaining the same final gear ratio), the chain's articulation angle will decrease.

An increase in the Articulation Rate will contribute to an *increase* in frictional losses. A larger ring, given the same cadence, will increase the articulation rate (chain links engaging/disengaging per second). The articulation rate can also be presented as a 'faster chain speed'. As the ring size increases, the tooth count per single rotation of the ring increases accordingly. One rotation of a larger ring will pull more links in that one rotation than a smaller ring, assuming rider cadence is held constant. For example, with a 39T front ring, 39 links are pulled through with one rotation of the crank. The articulation rate of a 39T front ring and 95 RPM cadence is 3,705 links per minute (39 x 95), or 61.8 links per second. Using the same rationale, with a 53T front ring and the same 95 RPM cadence, the articulation rate is 5,035 links per minute, or 83.9 links per second. As this example shows, a larger ring creates an increased articulation rate.

To combine the three mechanical functions- The decrease in frictional losses from the decreased top-span tension, in addition to the decrease in frictional losses from the decreased angle of articulation, in addition to the *increase* in frictional losses from the increased rate of articulation, the combined **net result** is an overall decrease in frictional losses with a larger ring.

The above explanation discusses the factors which affect frictional losses in the *top span* with a larger ring. A larger ring will also most likely affect the frictional losses in the bottom three chain spans. The effect is a small increase in frictional losses. However, the increase in the frictional losses in the bottom spans is relatively insignificant when compared to the decrease in frictional losses in the top span because of the large difference in the magnitude of chain tension between the top span vs the bottom spans (top being much larger). Nonetheless, the increase in the frictional losses in the bottom spans is measurable and should be considered in the discussion.

A larger ring will increase the frictional losses in the bottom three spans because of an increase in the rate of articulation. The bottom span analysis is more complicated than the top span since the bottom three spans contain a total of six unique engagement/disengagement points, as compared to two points associated with the top span. Going back to the general chain friction formula and applying it to the bottom spans will show why the increase in frictional losses occurs in the bottom spans. (1) Tension in the bottom three spans is constant because it is controlled by the derailleur cage tension, and not by rider power output. No tension changes occur with a larger ring. Therefore, the tension portion of the formula creates no increase nor decrease in frictional losses. (2) The articulation angles seen at the pulleys remain constant regardless of ring size. Yet, with a larger ring, the articulation angles decrease at the ring disengagement and cog engagement points on the bottom spans. However, (3) with a larger ring, the rate of articulation increases in all three bottom spans.

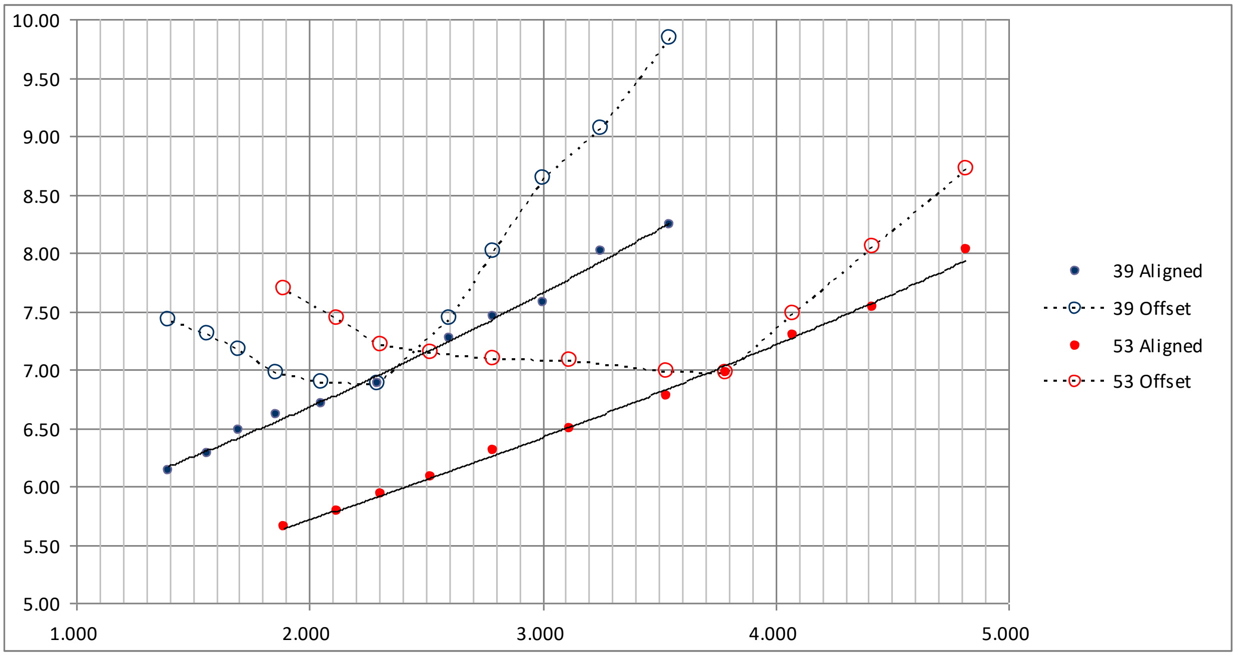
For the bottom spans, when the mechanical changes created by a larger ring are applied to the chain friction formula, (1) tension does not change, (2) two points of decreased articulation angle will contribute to decreased frictional losses. However, (3) six points of increased articulation rate will increase the frictional losses. The increased articulation rate will ultimately create an overall increase in frictional losses in the bottom spans.

It should also be noted that the increase in articulation rate (chain speed) will also cause the pulley bearings to spin faster. This, too, adds a small amount of friction.

Yet, when comparing the friction decrease in the top span vs friction increase in the bottom spans, the top-span decrease far outweighs the bottom-spans increase in friction. This is because the top span has approximately 50lbs of steady-state tension with a 53T ring, 95RPM, 250W rider output. The bottom spans have approximately 2lbs of tension going through two pulleys. The magnitude of difference between top span and bottom spans is roughly 25 times. Considering the top-span has two engagement/disengagement points, and the pulleys have a total of four engagement/disengagement points, the difference is now a factor of 12 times. I.e., the decrease in frictional losses realized in the top span by using a larger ring is 12 times greater than the increase in frictional losses seen in the bottom spans from using the same larger ring. Therefore, and as seen in the hard data, and in an actual drivetrain, when top and bottom spans are combined, the effect of using a larger ring is an overall decrease in total frictional losses.

How are the frictional losses affected by the size of the rear cog with the front ring size held constant? The data shows that decreasing the size of rear cog (increasing the effective final gear ratio), given the same front ring size, cadence, and power output, will increase the frictional losses. This can be seen visually in graph 4 by the positive slope of both rings (an increase in final gear ratio correlates to an increase in frictional losses). This friction increase is most likely due to the increased articulation angle of the rear cog disengagement point as cog size decreases. Chain tension and rate of articulation remain constant since front ring, cadence, and power output are constant. However, rear cog articulation angle increases, creating the increase in frictional losses.

Putting All Of The Data Together:



Graph 5 shows both the aligned curves and lateral misalignment V-curves for each ring superimposed. When comparing the aligned and misaligned data sets for a given ring, it is apparent that chain misalignment increases frictional losses, which can be seen in the delta between the aligned curves and misalignment V-curves at any given ring-cog combination, except for 39-17 and 53-14, where no misalignment occurs. At every ring-cog combination with misalignment, the same combination in an aligned manner always exhibited lower frictional losses.

Additionally, the frictional losses increase with an increasing angle of misalignment. This can be seen in the increasing delta between the aligned curves and the misaligned curves as the curves move right or left of the 39-17 and 53-14 point . As the amount of misalignment increases the difference in frictional losses between the misaligned and aligned conditions increase accordingly.

Finally, the purely aligned curves help to explain the slopes and rate of slopes of the misaligned data lines. The slopes of the misaligned V-curves are much steeper on the right arms of the curves than the left arms as the arms extend past the 39-17 and 53-14 points. This shows the rate of increase of frictional losses is much greater per rear cog shift when shifting into smaller cogs (right arm of V-curves) than when shifting into larger cogs (left arm of V-curves).

Take, for example, the misaligned V-curve of the 53T ring in Graph 5. The 53-14 data point is the gear combination that is naturally aligned on the bicycle and the point of intersection of the aligned and misalignment curves. I.e., when the chain is in the big ring, the cog in which the chain is most aligned (no apparent cross-chaining) is the 14T cog (4^{th} cog). The slope of the V-Curve extending to the right of the 53-14 combination is much steeper than the slope of the V-curve extending to the left of the 53-14 combination. On the drivetrain itself, even though each shift of the cog to the left or right of the 53-14 (going up or down the cassette) produces the same amount of lateral misalignment per shift, the rate of frictional losses increases at a much greater rate when shifting on the right side of the 53-14 (shifting in the smaller cog area of the cassette). This behavior can be explained by comparing the misaligned V-curves to the aligned curves. As stated previously, absolute magnitude of slopes of the right arms and left arms of the misaligned V-curves are not the same. That being said, the slope *differences* (rate of change) when *comparing* the right arms and left arms of the misalignment V-curves to right and left arms of the respective purely aligned curves are very similar. Therefore, the frictional losses due *only* to lateral misalignment, *with no contributions from cog size*, are similar whether moving left or right. However, when the frictional losses due to misalignment are factored in *together* with the frictional losses due to cog size, the V-curves become asymmetrical with respect to right and left sides.

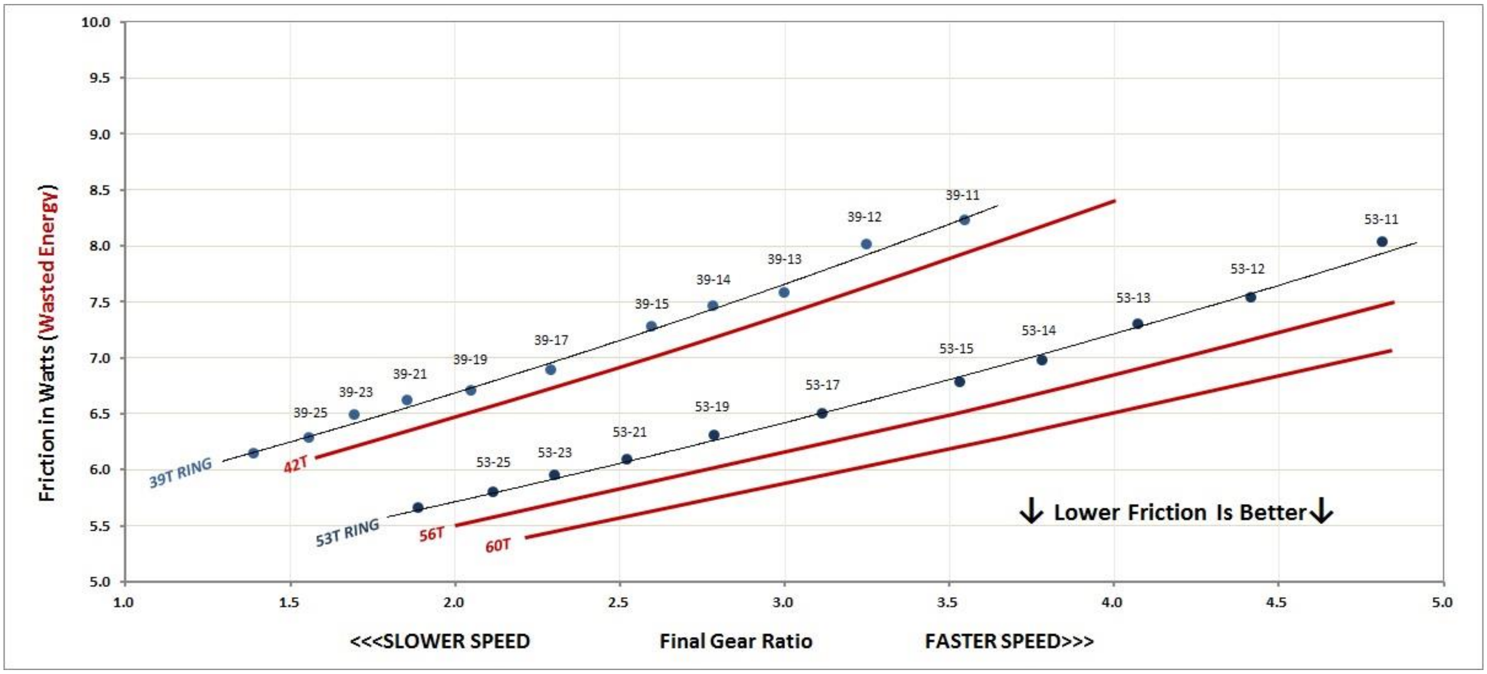
Essentially, the data shows that the total magnitude of frictional losses at any misaligned ring-cog combination is the <u>sum</u> of the effects of frictional losses of that ring-cog combination in the aligned state plus the effects of the specific angle of misalignment. The total magnitude varies whether the chain is in the smaller cog area of the cassette or larger cog area of the cassette.

In other words, when shifting into smaller cogs from the 53-14 position (moving right on the V-curve), the move to a smaller-sized cog *increases* friction, *and* the lateral misalignment also *increases* friction, resulting in relatively high frictional loss increases. Conversely, when shifting into larger cogs from the 53-14 position (moving left on the V-curve), the move to a larger-sized cog *decreases* friction, yet the lateral misalignment *increases* friction. The magnitude of the increase is greater than the magnitude of the decrease, resulting in an overall relatively small frictional loss increase.

How does chainstay length affect frictional loss levels? Chainstay length will affect the overall frictional losses of the drivetrain. Shorter chainstays, say, as seen on 650c bikes, create greater misalignment angles, therefore creating increased frictional losses during cross-chaining. Longer chainstays create decreased frictional losses during cross-chaining. The angular misalignment measurements for this test were based on a distance of 38.5cm from BB center to rear axle center.

Further Discussion-
Frictional losses of rings/cassette combinations other than the 53T-39T and 11T-28T combination used in this test

This test specifically used a 53T big ring, a 39T small ring, and an 11-28T cassette. Many other ring and cassette options exist. Practically speaking, how would frictional losses and optimal shift points change if different rings and/or cassettes are used?



Based on the results and curves obtained with the data, it is speculated that the frictional losses of ring and cassette combinations other than 53T, 39T, 11-28T can be determined, and new shift points found for the new combinations. In order to determine frictional losses of different combinations, the effects of different rings must be analyzed first, and the effect of different cassettes can then be analyzed.

Let us begin by studying the effects of different-sized sized rings. In graph 6 above, the aligned frictional loss curves of the 39T and 53T from graph 4 are shown in blue, and different ring curves have been added in red. The 42T, 56T, and 60T curve examples are based on extrapolation of the existing 39T and 53T curves X-Y equations. Based on these extrapolated curves, a 60T ring for example, would save approximately 0.75 watts when compared to a 53T ring, given the same final gear ratio.

Next, a different cassette must be analyzed. Practically speaking, if a larger ring is used, the cassette cog size must be increased to maintain the same final effective gear ratio. Alternatively, a rider may want to change to a wider range or narrower range cassette. Regardless, calculations must be performed for a different-sized cassette other than the 11T-28T.

Drawing a fresh graph with new aligned curves and new misalignment V-Curves is the best method to determine new frictional loss values. Starting with a blank graph, insert the new aligned ring curve on the graph, based on the extrapolated red curves in the above graph, or create a different new aligned curve by hand for a given ring size based on the extrapolation method.

Next, the intercept point of the to-be drawn V-curve and the new aligned ring curve must be determined. In order to do this, find the cog tooth size that naturally aligns with front ring on the bike. If the big ring V-curve is being created, the intercept will most likely be the 4th cog. If the small ring V-curve is being created, the intercept will most likely be the 6th cog.

Now, take the new chainring tooth count, and divide it by the tooth count of the cog which is in the naturally aligned position. The resulting number will be the final effective gear ratio of this naturally aligned combination, but more importantly, this will provide the point of intercept of the V-curve and the aligned curve on your new graph. On the x-axis, locate this new gear ratio, then place a dot on the new aligned curve at that intercepting point. This will be the bottom point of the new V-curve.

The new V-curve arms will extend upward to the left and right of this intercept point, in the same manner as the V-curve seen in graph 5. In order to create the new V-Curve arms, the first step is to determine the remaining 10 new ring-cog final gear ratios. This is accomplished by dividing the ring tooth-count by the 10 remaining new cogs tooth-count. Once the 10 new final gear rations are determined, place 10 dots on the aligned curve where the new gear ratios on the x-axis intercept the aligned curve. The graph at this point should look like one of the 11-dot aligned curves as seen in graph 4. Next, start at the dot representing the naturally aligned position. Move to the first dot to the left of the naturally aligned dot, and move that dot up 0.19 watts from the existing location. Then, for the second dot to the left, move that dot up 0.49 watts. For the third dot to the left, move it up 0.79 watts. For the fourth dot to the left, move it up 1.10 watts. For the fifth dot, move it up 1.40 watts. For the sixth dot, move it up 1.70 watts. For the seventh dot, move it up 2.01 watts. Repeat this process for the dots to the right of the aligned dot. When a smooth curve is drawn through all of the new dots, a distinctive V-curve should emerge. Note, the above wattage increases represent the increase in frictional losses due only to lateral misalignment for each cog step. 7 cog steps are provided for reference, yet all 7 might not be needed to complete a single side of the V-Curve. For example, if the 53 ring is naturally aligned in the 4th cog, only three steps will be needed when drawing the right side of the V-Curve; steps for cog 3, cog 2 and cog 1.

Cog Misalignment (number of cogs left or right from aligned state)	Frictional Losses in Watts due only to the effect of lateral misalignment
1	0.19
2	0.49
3	0.79
4	1.10
5	1.40
6	1.70
7	2.01

Repeat this process for the small ring to create a misaligned V-Curve for the small ring.

The crossover point of the two newly drawn misaligned V-Curves for the small and big rings will be the new optimal shift point between the big and small rings.

Beyond Optimal Shift Points-
Tailoring the rings and cassettes to the race course

Aside from providing optimal shift points, the results of this test provide a few important takeaways which can be applied to selecting the most efficient rings and cassette based on a specific race course.

If a race course, say a time trial, is relatively flat, and the rider will spend a majority of the race time within a narrow speed window, the benefits of tailoring are more easily achieved.

Example: Tailoring Track Bikes
Track bikes are set up in an optimal manner. The course is perfectly flat and without wind. The final gear ratio (ring-cog combination) is determined based on the rider's power output, cadence, and desired attainable average speed for the race. The largest practical ring would be used on the bike, with a corresponding cog to achieve that optimum final gear ratio.

Track bikes and tracks are best-case scenarios. Most non-track road races and TT's are not perfectly flat courses and are susceptible to wind. Derailleurs must be used since various gear ratios might be necessary for varying grades and accelerating out of corners. Yet, if the course is such that a typical speed is carried for most of course, the gear ratios that will accommodate this speed can be placed in the position of the cassette that will have the least amount of frictional losses. The typical speed will be referred to as the 'majority speed range' for the explanation below.

Based on Graph 2, the lowest area of frictional losses across the higher-speed range of gears occurs at the flat area of the green shift sequence line; when the big ring is in the 4^{th}, 5^{th}, and 6^{th} cogs. Therefore, it would behoove a racer to have the chain located in one of these 3 cog positions when the rider is in the 'majority speed range'.

Note- The results of this test show larger rings are more efficient. The short-sited action to decrease drivetrain friction based upon the results might be to simply install bigger rings. However, if the cassette cog-size range is not also considered, the installation of a larger front ring will cause a rider to have to use a larger cog to maintain the similar final gear ratio. If use of a larger cog also creates additional levels of cross chaining (ie, the chain is taken higher up the cassette to maintain the same final gear ratio) then this could negate the advantage of using a larger ring. Therefore, it is important to look at both the ring size and cassette range before changing rings and cassettes.

To tailor the rings and cassette, first determine the "majority speed range" for the course. Using the speed and the rider's preferred cadence, determine the final gear ratio range that will accommodate the 'majority speed range'. Select the largest ring size which is practical. Knowing the tooth-count of the ring, determine the cog sizes necessary to accommodate the 'majority speed range'. These cog sizes should then be placed in the 4^{th} 5^{th} and 6^{th} position. Determine the slowest speed for the course, and ensure the large cog on the cassette w/the small ring will accommodate this speed. Determine the fastest speed for the course, and ensure the small cog w/the big ring will accommodate this speed. This will provide the size of the 11^{th} cog, the size of the 1^{st} cog, and the sizes of the 4^{th}, 5^{th}, and 6^{th} cogs. The remaining cogs can be sized accordingly to provide a smooth range between the 1^{st} and 4^{th} and 6^{th} and 11^{th} cogs.

Granted, the above approach is a best case scenario for cog selection. Many cassettes will not accommodate individual cog size changes. The key takeaway is to run a larger big ring, while adjusting the cog sizes so the chain is positioned for the majority of the race in the 4th and 5th cog position.

Hypothetically Speaking:

The data trends presented in this report suggest frictional losses are minimized with larger ring sizes paired with large cogs. This begs the question, if a racer is presently using a 53T ring with an 11T-28T cassette, would it make sense to use a 106T ring, with a 22T-56T cassette? From a frictional loss standpoint- the answer is Yes. For all of the reasons explained in this report, this setup should decrease friction substantially, and yet still maintain the same final gearing. The aligned curves for the rings would move down and to the right. The V-curves would then move down and to the left. That is, to ultimately move downward on the Y-Axis of frictional loss.

While this would be very efficient on paper, some of the potential disadvantages of a set up like this would be potential flex in the larger ring, potential weight increase of the larger ring and cassette, potential increased aerodynamic drag from the increased frontal area of the ring, and increased weight due to the need for a longer chain. Additionally, most racers are limited to commercially available rings and cassettes. A middle ground would have to be chosen with regard to ring size which minimizes friction, yet still remains practical.

Data:

Cog #	**Cog Teeth**	**Ring Teeth**	Gear Ratio	Aligned or Offset	Offset mm	Offset Angle	Shimano Chain Watts	SRAM Chain Watts	**Average Losses Watts**
1	**11**	**39**	3.55	Offset	19.5	2.90	9.89	9.79	**9.84**
2	**12**	**39**	3.25	Offset	15.6	2.32	8.96	9.16	**9.06**
3	**13**	**39**	3.00	Offset	11.7	1.74	8.49	8.79	**8.64**
4	**14**	**39**	2.79	Offset	7.8	1.16	8.05	7.99	**8.02**
5	**15**	**39**	2.60	Offset	3.9	0.58	7.47	7.41	**7.44**
6	**17**	**39**	2.29	Offset	0	0	6.92	6.86	**6.89**
7	**19**	**39**	2.05	Offset	3.9	0.58	6.97	6.81	**6.89**
8	**21**	**39**	1.86	Offset	7.8	1.16	7.01	6.93	**6.97**
9	**23**	**39**	1.70	Offset	11.7	1.74	7.29	7.07	**7.18**
10	**25**	**39**	1.56	Offset	15.6	2.32	7.43	7.17	**7.30**
11	**28**	**39**	1.39	Offset	19.5	2.90	7.51	7.35	**7.43**
1	**11**	**53**	4.82	Offset	11.7	1.74	8.76	8.68	**8.72**
2	**12**	**53**	4.42	Offset	7.8	1.16	7.98	8.12	**8.05**
3	**13**	**53**	4.08	Offset	3.9	0.58	7.36	7.60	**7.48**
4	**14**	**53**	3.79	Offset	0	0	6.89	7.05	**6.97**
5	**15**	**53**	3.53	Offset	3.9	0.58	6.94	7.02	**6.98**
6	**17**	**53**	3.12	Offset	7.8	1.16	7.16	7.00	**7.08**
7	**19**	**53**	2.79	Offset	11.7	1.74	7.24	6.96	**7.10**
8	**21**	**53**	2.52	Offset	15.6	2.32	7.30	6.98	**7.14**
9	**23**	**53**	2.30	Offset	19.5	2.90	7.42	7.00	**7.21**
10	**25**	**53**	2.12	Offset	23.4	3.48	7.76	7.12	**7.44**
11	**28**	**53**	1.89	Offset	27.3	4.06	7.90	7.48	**7.69**

Cog #	**Cog Teeth**	**Ring Teeth**	Gear Ratio	Alligned or Offset	Offset mm	Offset Angle	Shimano Chain Watts	SRAM Chain Watts	**Average Losses Watts**
1	**11**	**39**	3.55	Aligned	0	0	8.17	8.31	**8.24**
2	**12**	**39**	3.25	Aligned	0	0	7.96	8.06	**8.01**
3	**13**	**39**	3.00	Aligned	0	0	7.55	7.61	**7.58**
4	**14**	**39**	2.79	Aligned	0	0	7.43	7.47	**7.45**
5	**15**	**39**	2.60	Aligned	0	0	7.29	7.25	**7.27**
6	**17**	**39**	2.29	Aligned	0	0	6.92	6.86	**6.89**
7	**19**	**39**	2.05	Aligned	0	0	6.80	6.62	**6.71**
8	**21**	**39**	1.86	Aligned	0	0	6.72	6.50	**6.61**
9	**23**	**39**	1.70	Aligned	0	0	6.54	6.44	**6.49**
10	**25**	**39**	1.56	Aligned	0	0	6.35	6.21	**6.28**
11	**28**	**39**	1.39	Aligned	0	0	6.15	6.13	**6.14**
1	**11**	**53**	4.82	Aligned	0	0	7.87	8.19	**8.03**
2	**12**	**53**	4.42	Aligned	0	0	7.43	7.65	**7.54**
3	**13**	**53**	4.08	Aligned	0	0	7.13	7.47	**7.30**
4	**14**	**53**	3.79	Aligned	0	0	6.89	7.05	**6.97**
5	**15**	**53**	3.53	Aligned	0	0	6.68	6.88	**6.78**
6	**17**	**53**	3.12	Aligned	0	0	6.47	6.51	**6.49**
7	**19**	**53**	2.79	Aligned	0	0	6.32	6.30	**6.31**
8	**21**	**53**	2.52	Aligned	0	0	6.11	6.05	**6.08**
9	**23**	**53**	2.30	Aligned	0	0	5.96	5.92	**5.94**
10	**25**	**53**	2.12	Aligned	0	0	5.77	5.81	**5.79**
11	**28**	**53**	1.89	Aligned	0	0	5.73	5.57	**5.65**