FRICTION FACTS

Friction-Producing Mechanisms of a Bicycle Chain

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Effectiveness of Chain Lubricants for Reducing Frictional Losses

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Overview

The friction-producing mechanisms of a bicycle chain moving through a derailleur-style drivetrain are unique and relatively complex. These friction-producing mechanisms arise from friction created in individual links, which are subjected to multiple regions of both high and low pressure, reciprocating sliding forces, and stiction. As such, testing methods for chain efficiency and chain lubricants must address these complex mechanisms.

This paper explores the details of how friction is created in a bicycle chain in a modern-derailleur style drivetrain, the role of chain lubricants to minimize friction in a chain, and the limitations of commonly-used friction test methods. This paper also suggests a testing process to analyze the efficiency of a chain and lubricant in a manner specifically relevant to chain friction-producing mechanisms.

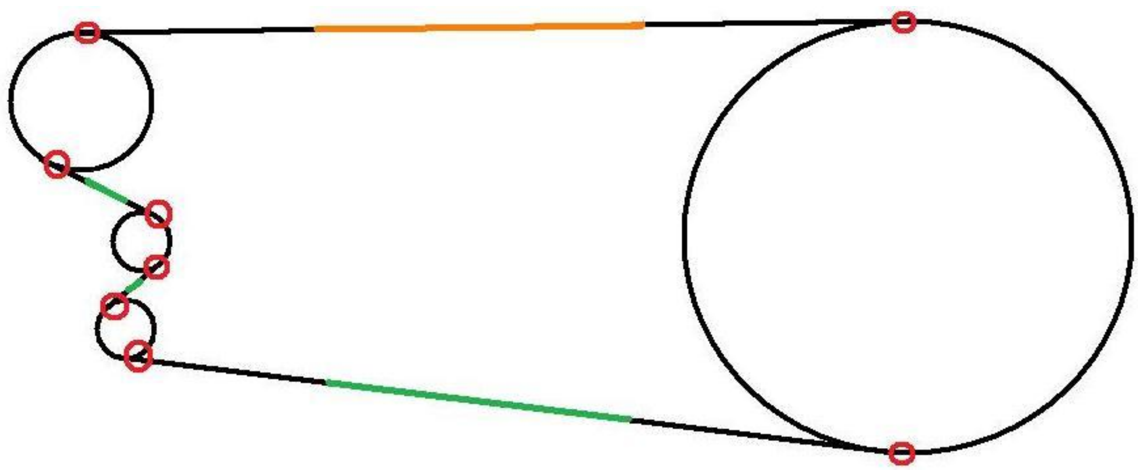
Friction-Producing Mechanisms of a Chain

From a simplified standpoint, the friction created (wasted energy) by a roller chain is generally proportional to: [chain tension] x [sine of lateral deflection] x [link articulation angle at a given engagement or disengagement point] x [number of link articulations per unit time at that point] x [total engagement and disengagement points in the complete drivetrain]. This basic formula has been demonstrated by multiple drivetrain studies and, more recently, by tests performed by Friction Facts.

Essentially, friction is created each time an individual link, under a finite level of tension, bends (articulates) as it engages or disengages the teeth of a cog, pulley, or chainring. Total chain friction can be viewed as the sum of the friction created by all of the links' engagements/disengagements as the chain snakes through the front chainring, derailleur pulleys, and rear cog. Tension, link articulation angle, link articulation rate, and lateral deflection (aka cross chaining) are directly proportional to the total friction losses of a chain.

As each link moves through the drivetrain, it is subjected to varying tensions and articulation angles. As a result, in a complete revolution through the drivetrain, the contributing friction at each of the engagement and disengagement points must be analyzed discretely and subsequently summed to determine the total friction created by the moving chain. (Please note: a "revolution" refers to a single revolution of the complete chain, not a single rotation of the pedal crank.)

A derailleur-style drivetrain contains a total of eight engagement and disengagement articulation points. See diagram below. The link articulation points associated with the top chain span experience generally high tension levels, as this span is responsible for transferring the rider's power to the rear cog. The link articulation points associated with the bottom chain span and the two short chain spans within the rear derailleur generally experience much lower tension, as the tension in these three spans is created by the force of the spring-loaded rear derailleur cage. In fact, this force on the bottom spans is independent of rider power output. Even though the tension of the bottom three spans is significantly lower than that of the top span, the friction created in the bottom chain spans must not be dismissed, since the bottom spans contain six friction-producing articulation points, whereas the top span contains only two points. Additionally, four of the six points are typically associated with the relatively small 11 tooth derailleur pulleys, which create high angles of chain articulation.



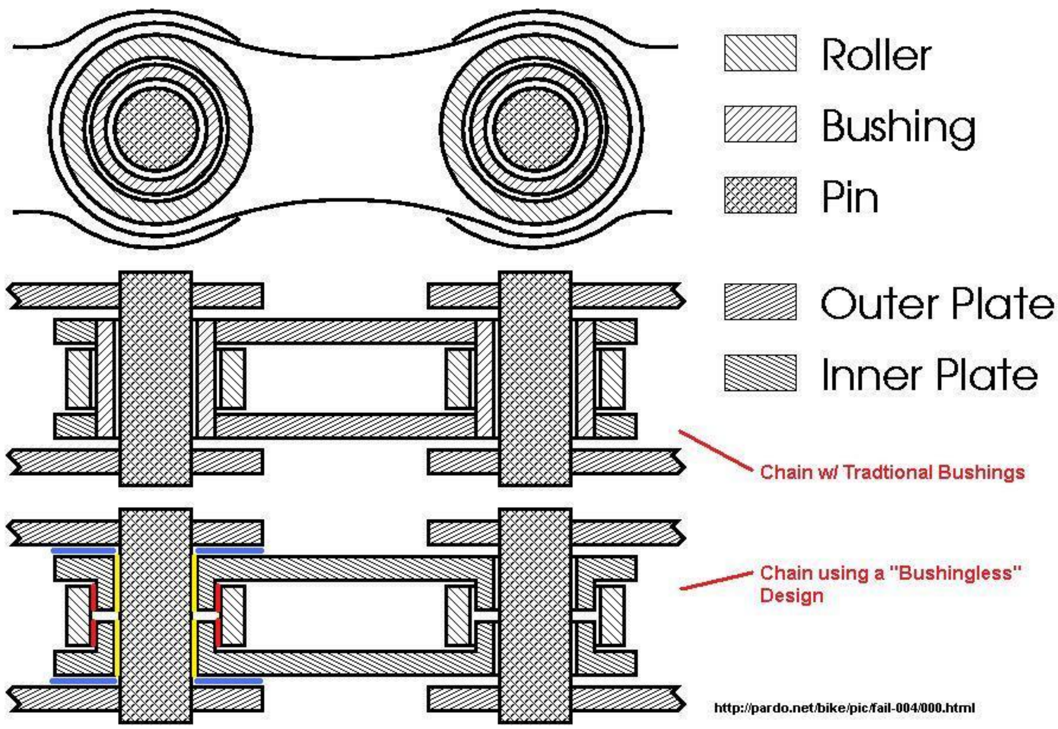
Red circles indicate the eight friction-producing engagement/disengagement points. The yellow top span typically experiences higher tension from rider power output. The three green bottom spans see lower tension, typically about 4 lbs for stock derailleur cages. Tension in the lower spans is fixed via the derailleur spring.

An often overlooked operational characteristic of a chain is that it is actually a *system* made up of many *reciprocating* links moving “back and forth”. This type of movement is very different than a truly continuous, steady-state revolving or rotating part, such as bearings or gears. When viewed as a *complete system* a chain, by definition, could be considered a single revolving entity. Yet, each link is a *reciprocating component* of the whole chain itself, lending to the steady-state condition of the whole chain. To reiterate this important concept, the frictional losses of an entire chain are due to the *total of the individual* reciprocating links’ frictional losses, and should be viewed as such when evaluating the friction mechanisms of a chain and accompanying lubrication of the respective reciprocating parts.

Another simple yet important attribute to consider is that a link itself never makes a complete rotation against an adjacent link. A given link can articulate to a maximum of 36° upon engagement, and back to 0° upon disengagement (in the case of a 10T cog or pulley). A link can also experience a negative 36° articulation as it engages and disengages the upper pulley. Therefore, a link can experience a maximum total articulation of 72°, but never a complete rotation.

Sliding Mechanisms within a Single Chain Link

Generally speaking, an individual link contains three unique areas of sliding surfaces, all of which contribute to the total friction created within each link.



The first of three sliding surfaces is the interaction of the central pin and plate shoulders (the yellow highlight in above pic). In older “bushing-style” chains, the so-called bushing pivots against the pin. In modern 10 and 11 speed chains, a “bushingless” design is used, where the bushing is removed, and functionally replaced by plate shoulders. The plate shoulders, which are part of the inner side plates, pivot against the pin rather than the separate bushing in the old design.

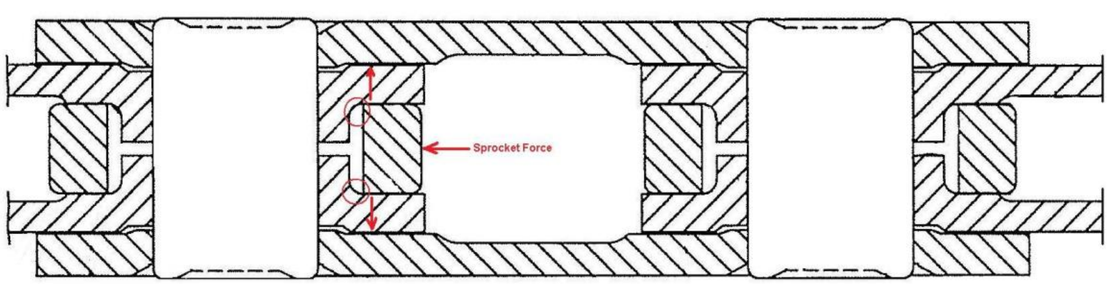
The second sliding surface is the interaction of the roller and plate shoulders (the red highlight in the above pic).

As a link enters a cog, ring or pulley, the above two sliding surface interactions occur in an alternating manner, depending on whether an inner or outer side plate is entering at that given moment. When a link enters with the inside plates on the tooth the high pressure internal sliding occurs at the roller/ plate shoulder interface. When a link enters with the outside plates on the tooth the high pressure internal sliding occurs at the plate shoulder/ pin interface.

The above description is for a chain with perfect pitch. In the case of an elongated (worn or "stretched") chain, the roller slides on the plate shoulders at EVERY engagement/disengagement point, not just alternating points, at a rate proportional to the amount of chain elongation. This is due to the tooth pulling the elongated chain (via the roller) *into* the tooth trough at every point. On a side note, this is one of the reasons an elongated chain is less efficient than a new chain with a perfect pitch; the teeth have to pull an elongated chain into the sprocket, creating additional (and unnecessary) friction.

The above mentioned two sliding surfaces can experience relatively high pressure, as the full chain tension due to rider power transfer is supported by these two surfaces. It should also be noted that these surface interfaces are cylindrical in shape. Because of the cylindrical geometry, the pressure at the interfaces is not constant across the entire sliding-surface area. At any given chain tension, the pressure will be at a maximum along the front edges of the interfaces which are perpendicular to the direction of chain tension. The pressure will then taper to zero at a point around the circle where the sliding interface is parallel to the direction of chain tension. In summary, these sliding interfaces experience pressure ranging from 0 to maximum depending on the location around the internal cylinder shape. This is of importance as the effectiveness of a lubricant varies with pressure.

The third sliding surface is the interface between the inner and outer side plates (the blue highlight in the above pic). This interface typically experiences low pressure conditions, unless heavy cross-chaining is occurring. Additionally, the side plate interfaces will experience higher friction if the bushingless chain is of a design where the force of the tooth on the roller creates a "wedge effect" pushing the inner side plates outward and therefore into the outer side plates. The drawing below is from a 2012 patent of an 11sp chain design, and provides an excellent example of why this effect occurs. Note the chamfered inner corner of the plate shoulders (red circles). This chamfer creates the "wedge effect" which effectively increases the pressure between the inner and outer plate sliding interfaces, when tension is applied by the tooth.



Stiction

When considering the friction created by the three sliding surface areas above, it is very important to recognize the fact that **stiction** (static friction) plays a very important role in overall chain friction. The effects of stiction due to the reciprocating nature of the chain are often overlooked. Stiction is a simple, yet important property exhibited in all sliding materials. When two sliding parts stop-start against each other (e.g., reciprocation of the chain links), static friction is created. Stiction is the 'sticking' together of two parts due to static friction; the force required to 'break' the two parts apart to then allow sliding. Once the two parts break free and are sliding against each other, the static friction becomes dynamic friction. Stiction is a 'threshhold' friction. Stiction must be overcome prior to the physical movement of the two parts, or in this case, the pivoting of a chain link.

<u>The friction created by stiction forces is always greater than the friction created by the subsequent dynamic friction.</u> As such, the stiction threshold of a link as it engages or disengages is greater than the subsequent dynamic friction in the link as it pivots in to or out of the ring/cog/pulleys. As an example, a drivetrain with a 53T front ring, at 95RPM rider cadence, produces **over 40 thousand stiction events every minute while riding**. Given the number of stiction events in a moving chain, and the fact that stiction is always greater than dynamic friction, frictional losses due to stiction are paramount and must not be overlooked.

(Friction is also created by the interaction of the teeth and the chain side plates, especially during cross chaining events. However, this type of friction is external to the chain itself, and is not analyzed in this paper.)

What Makes a Highly Efficient Chain Lubricant?

In order to achieve low overall frictional losses, and thus high efficiency, a chain lubricant must perform well in three discrete areas -- high pressure sliding conditions, low pressure sliding conditions (lubricant surface tension and viscous drag mostly dictates friction levels in this low pressure area), and reciprocating conditions, in which stiction is the major factor. A lubricant that performs extremely well in one condition, but very poorly in the other two, could potentially be less efficient than a chain lubricant demonstrating mid-level performance in all three conditions. For example, many chain lubricants claim exceptional high pressure performance, and many contain special additives such as "extreme pressure additives". While that may be, the high pressure sliding areas are just one of three friction producing areas.

To illustrate the efficiency difference between two lubricants, a frictional loss comparison analysis could be performed on a thin oil and a heavy grease (hypothetical lubricants in this example). We'll assume both of these lubricants perform similarly (and extremely well) in the standard ASTM high pressure wear tests. When either of these lubes is applied to a chain, both of them will perform very well in the high pressure zone of the front face of the pin/plate shoulder and plate shoulder/roller interface within the link. Yet this is only part of the picture. If we assume the higher viscosity grease has a higher surface tension than the oil, then the grease will perform more poorly in the low pressure interface areas of the link (ie, the side plate interactions and the interactions of the parallel surfaces of the pin/plate shoulders and plate shoulders/roller). Additionally, we'll assume the grease has inherently more stiction force than the oil. When all three performance characteristics of the grease and oil are combined, the thin oil will create less total chain friction than the grease.

Because of the combined effects contributing to overall chain friction, it is important for a chain lubricant to excel in all areas, not just the high pressure area.

It is important to note at this point- the "wear" properties of a lubricant are not necessarily indicative of the frictional losses or efficiency of a lubricant in the case of bicycle chains. Logically, it would seem that these two properties would always correlate, since frictional losses are created when two materials slide against each other and material loss, or wear, occurs. Hence, increased wear would equate to greater overall frictional loss of the chain. But this is not always the case.

Indeed, wear can create frictional losses, but in a chain, frictional losses can also be created by mechanisms not associated with wear, nor by mechanisms producing wear. For example, in the hypothetical situation above, a portion of the overall friction is created by the fluid resistance of the high viscosity grease. This type of friction is based solely on fluid dynamics properties, and no metal-metal wear occurs. All frictional losses of this type are created within the grease itself due to fluid shear forces. A simple experiment illustrates this effect. If one were to take two thin, flat, and DRY metal plates, and stack the two plates on a table, and then slide the top plate against the bottom plate, then back and forth, they would slide against each other relatively easy. If the same procedure was followed, but this time a layer of viscous grease was applied between the plates, it would take more force to slide the greased plates back and forth than the dry plates. The greased plates take more linear force to slide, and therefore more frictional losses are created. In most industrial situations, the application of grease to two metal sliding surfaces decreases frictional losses. In this case however, the grease increases the frictional losses. Yet, the wear of the dry plates would be greater than the wear of the greased plates. The takeaway is frictional losses do not necessarily correlate to wear.

"Wear" and "chain life" can be used synonymously in this paper. As such, chain efficiency and chain longevity are not necessarily related either. A chain lubricant which provides for a long chain life might not be the most efficient lubricant. Chains elongate, in the most part, due to material wear on the front face of the relatively smaller diameter pin/plate shoulder interface (the yellow area in the above pic). A lubricant with excellent wear performance would minimize chain elongation and maximize chain longevity, yet could perform poorly in other friction areas, lending itself to poor efficiency. If a cyclist would desire a lubricant that extends the life of the chain, a lubricant with good wear test results should be chosen. If a cyclist would like a lubricant that offers high efficiency, a lubricant with good efficiency test results should be used. This is not to say that a lubricant can't perform well in both categories of tests, it is to say that different tests provide different information.

In summary- for a chain lubricant to achieve high efficiency, the combined effects of the lubricant's performance in the three basic friction-producing mechanisms must be considered. These are the high pressure region, low pressure region (dominated by the surface tension and viscosity characteristics of the lubricant), and stiction effects. A lubricant may be very effective when tested under only high pressure conditions. However, that same lubricant may not perform well with regard to the effects of low pressure surface tension, and/or the effects of stiction, and therefore might exhibit low overall efficiency.

Why is Paraffin Wax an Extremely Effective Chain Lubricant?

Readily available, food-grade (99.5% pure (see FDA 172.866)) paraffin wax with additives is the most efficient chain lubricant tested as of the date of this paper. Yet paraffin is rarely used in industrial applications for lubrication. So, why is paraffin so effective at minimizing chain friction? It is speculated this is due to its superior low pressure and stiction performance.

While paraffin wax is actually a long-chain saturated hydrocarbon derived from crude oil, its performance in high-pressure areas is most likely average when compared to other specialized lubricants designed for high pressure.

Yet, when paraffin wax is evaluated in the two other friction-producing areas, the performance advantages begin to emerge. Since paraffin wax is a dry material, the surface tension of the wax-on-metal sliding interfaces is much lower (or close to non-existent) than that of a liquid lubricant. This minimizes the friction contribution in the low pressure regions. Also, the stiction properties are most likely favorable to wax, as the wax forms a cohesive, solid, and dry boundary layer within the asperities of the metal surface.

When these three characteristics of paraffin are combined; excellent performance in low pressure sliding regions, excellent performance with regard to stiction, and average performance in high pressure sliding regions, the result is a lubricant that provides *overall* superior performance.

Friction Facts has tested many extremely efficient lubes, with measured efficiency levels very close to that of paraffin wax. Paraffin was chosen as an example not only because it is presently the most efficient chain lubricant, but because of paraffin’s unique material properties and non-traditional role as a lubricant, when compared to other traditional liquid-style chain lubricants.

Test Method Specifically Designed to Test the Efficiency of Chains and Chain Lubricants

When determining the efficiency of a chain and/or the chain lubricant, it is important that a test method specifically designed to test chains is used. When the chain itself is tested, this inherently tests the affects of the three friction producing mechanisms and therefore the realistic efficiency level of the lubricant. Additionally, a test method should closely simulate the bicycle drivetrain from a mechanical standpoint.

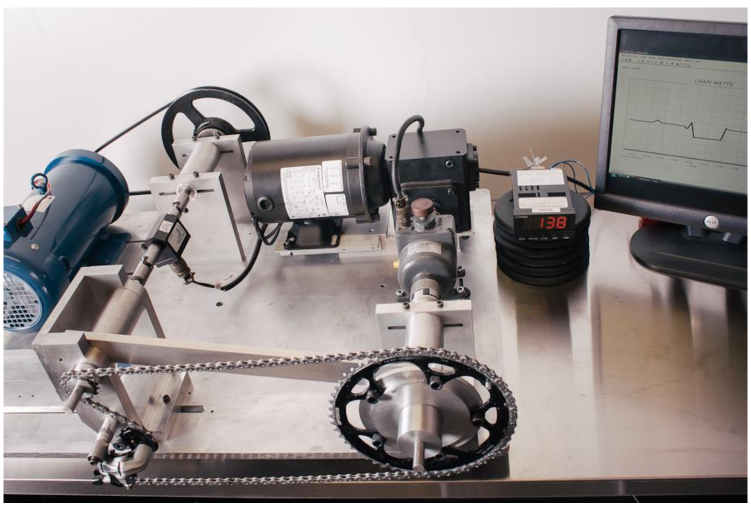
Friction Facts often receives feedback from lubricant manufacturers stating their own independent testing results do not agree with Friction Facts’ efficiency tests results. The differences in results between manufacturers’ tests and Friction Facts’ tests are most likely due to the fact that lubricant manufacturers utilize test methods designed to detect *wear* in rotating components such as ball, roller, and sleeve bearings, or gearboxes, while Friction Facts uses test equipment specifically designed to test the *efficiency* of chains. Albeit traditional lubricant wear and friction test methods are highly regarded, time proven, and accurate ASTM (astm.org) and ANSI (ansi.org) certified testing methods, these methods do not simulate the mechanical functionality of a bicycle drivetrain. They were not created nor were they designed to test the efficiency of a bicycle chain and the reciprocating chain link. As discussed earlier, wear and efficiency do not always correlate in a chain.

For example, the common ANSI Falex, Four-Ball, and Timken wear-tests analyze sliding surface wear under steady state rotating conditions, constant pressure, and often with the sliding surfaces immersed in a bath of the subject lubricant. Additionally, some of the test equipment can analyze torque requirements (ie, friction). However, chain links are not steady state rotating components. As indicated before, they reciprocate. Furthermore, chains are not immersed in a bath of oil *while* being ridden. Bicycle chains rely on a layer of lubrication held by surface tension to the metal surfaces and do not have the advantage of being immersed in an oil bath. Chain friction is heavily affected by stiction, which these tests do not analyze. Manufacturer wear tests provide only a portion of the overall picture, and these traditional tests lack important functionality to test the friction-producing mechanisms of a real-world bicycle chain.

A newer piece of test equipment, the High-Frequency Reciprocating Rig (HFRR) analyzes friction with a reciprocating flat surface contact patch. It was designed to test the wear properties of lubricants in magnetic coil fuel injectors. While HFRR testing more closely simulates the reciprocating operation of a chain than the above-mentioned steady-state rotating test methods, this test method still possesses limitations. The contact patch is flat as opposed to being circular, and subjects the sliding surfaces to a single constant pressure rather than a range of varying pressures across the given sliding surface, as seen in articulating chain links.

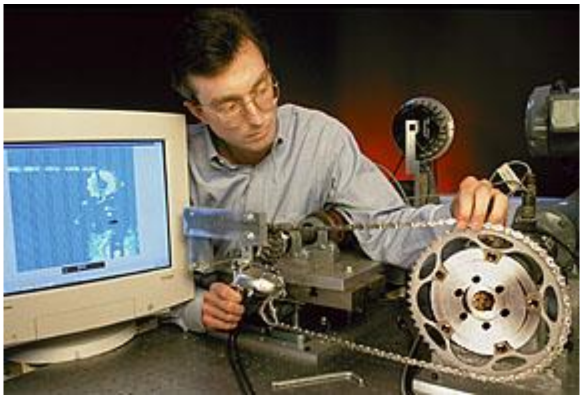
In an effort to create test equipment capable of measuring chain efficiency, Friction Facts, and a few other university labs have utilized what is called the “Full Load Test Method”. This test method replicates a bicycle drivetrain very closely. It uses rotating power on the front axle, simulating a rider pedaling, and a rotating load on the rear axle, simulating rear wheel load, with a full derailleur cage in the system. Essentially, torque is measured at the front drive axle and the rear load axle. The difference between these two torque measurements is the frictional losses of the drivetrain.

Additional details of the Friction Facts full load tester can be found here:
http://www.friction-facts.com/equipment/chain-full-load



Friction Facts’ Full Load Tester

Additional details of the equipment Spicer et al used in his popular chain efficiency paper can be found here: http://www.ihpva.org/HParchive/PDF/hp50-2000.pdf



Spicer with his test rig (www.jhu.edu)

While the Full Load Test Method most closely simulates the real-world functional operation of a bicycle drivetrain, the precision of this test method is limited. Since the equipment's precision and full-scale range is designed to accommodate full rider power output (say, for example, 250 watts), small variations (fractions of a watt) in the drivetrain friction are difficult to discern.

In order to achieve a level of measurement precision necessary to analyze chains and chain lubricants, and new test method was designed. This test method uses symmetrical tension applied to the chain to simulate the tension seen in the asymmetrical Full Load Tester. While the Full Tension Test Method does not replicate the bicycle drivetrain as closely as the Full Load Test Method, it is 10 times more precise and still measures the actual chain friction and the affects of the three friction producing mechanisms of the chain. The precision of the Tension Test Method is +/- 0.02 watts compared to the Full Load Test Method at +/- 0.25 watts.

Additional details of the Tension Test Method can be found here:
http://www.friction-facts.com/equipment/full-tension-test-method

